

ON THE RELATIONSHIP BETWEEN AMBIENT PRESSURE CHANGES AND INNER EAR HYDRODYNAMICS

A new way to control Meniere's disease?

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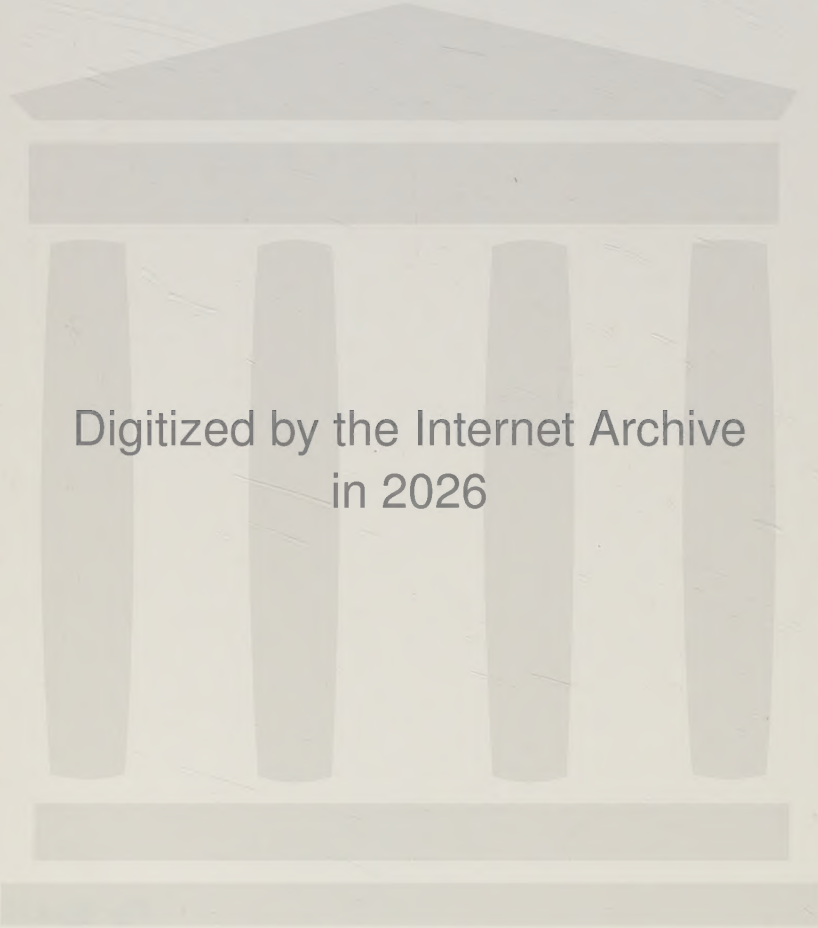
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This thesis is based on the following papers which in the text will be referred to by their Roman numerals.

- I. Transmission of square wave pressure pulses through the perilymphatic fluid in cats.
Acta Otolaryngol (Stockh) 1986. Accepted for publication
(B. Densert, O. Densert, B. Erlandsson and H. Sheppard)
- II. Study of the transmission of complex pressure waves through the perilymphatic fluid in cats.
Acta Otolaryngol (Stockh) 1986. Accepted for publication.
(B. Densert, O. Densert, B. Erlandsson and H. Sheppard)
- III. Quantifying psychoacoustic tuning curves for clinical use.
Scand Audiol 1986. Accepted for publication.
(B. Densert, B. Kinberger, S. Arlinger and O. Densert)
- IV. Effects of overpressure on hearing function in Meniere's disease.
Acta Otolaryngol (Stockh) 1986. Accepted for publication.
(B. Densert)
- V. Air-bone gap in Meniere's disease after exposure to overpressure.
Submitted to Audiology 1986.
(B. Densert, S. Arlinger and O. Densert)

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GENERAL INTRODUCTION

Meniere's disease is an inner ear disorder which, despite extensive research, is still a subject of controversy. The aetiology of the disease and the exact mechanisms eliciting the symptoms are not fully understood and available methods of treatment have not proven satisfactory.

Because of the lack of non-invasive techniques, it has not been possible to study directly, in vivo, the inner ear hydrodynamics in humans. Therefore, the concept that the inner ear symptoms in Meniere's disease are caused by endolymphatic hydrops, is based on morphological observations from fixed specimens of temporal bones (Hallpike & Cairns, 1938; Schuknecht & Gulya, 1983; Paparella, 1984). Absence of morphological signs of hydrops has also been reported in temporal bones from patients with a clinical history of Meniere's disease. On the other hand, morphological evidence of endolymphatic hydrops has been found in patients without any previous history of episodic vertigo or hearing loss. Endolymphatic hydrops has also been associated with inner ear disorders caused by embryopathic, inflammatory and traumatic factors. This large group of inner ear conditions has been known as Meniere's syndrome and separated from the idiopathic endolymphatic hydrops, which is called Meniere's disease (Schuknecht & Gulya, 1983; Paparella, 1984).

Clinically, Meniere's disease is characterized by recurrent attacks of vertigo, fluctuating hearing loss in the early stages, tinnitus and fullness in the affected ear. Hallpike & Cairns (1938) formulated the hypothesis that the symptoms in Meniere's disease were caused by an increased endolymphatic pressure within the maximally dilated membranous labyrinth. Their hypothesis was based on morphological findings of dilatations, ruptures and herniations of the inner ear membranes. Other investigators have questioned that there is a pressure gradient across Reissner's membrane (Allen, 1983). Due to difficulties involved with measurements of the endolymphatic pressure, there is still no evidence that the endolymphatic pressure exceeds the perilymphatic pressure in cases of endolymphatic hydrops.

Meniere's disease is only known to exist in humans. In animals, endolymphatic hydrops was first produced experimentally by Kimura & Schuknecht (1965) by blockage of the endolymphatic duct. This animal model has also been used by others for studies of inner ear fluid dynamics (Kishimoto et al., 1983). The procedure demonstrated that accumulation of endolymphatic fluid, following blockage of the endolymphatic duct, resulted in similar morphological changes in the inner ear membranes to those found in human temporal bones from

subjects who had suffered from Meniere's disease. The results from these studies indicated the importance of the function of the endolymphatic duct and sac for maintenance of the inner ear fluid balance. Attention has been focused on the endolymphatic sac as the organ important for reabsorption of endolymph (Guild, 1927; Lundquist, 1965; Friberg et al., 1985). It is debated, however, whether the morphological findings of tissue degeneration around and within the walls of the sac may count as evidence of malfunction of the sac, or should be considered secondary to the endolymphatic hydrops (Schindler, 1979).

Tonndorf (1975), in his classical experiments on cochlear models, found that an increase in size of the scala media caused biasing of the apical portion of the basilar membrane which could explain the mechanisms of low-frequency hearing loss and cochlear distortion in the early stages of Meniere's disease. The mechanism of the flat hearing loss in advanced stages of Meniere's disease is not fully understood. Tonndorf assumed that the sensorineural hearing impairment is caused by an increase in the mass of the cochlear duct and permanent stretching of the inner ear membranes.

Experience from morphological investigations, cochlear models and animal experiments thus indicates that the symptoms in Meniere's disease originate from a disturbance in the volume/pressure relation of the inner ear fluids.

Medical and surgical methods have been aimed towards decreasing the volume of the endolymphatic fluid (Arenberg et al., 1983; Maddox, 1983). The development of endolymphatic sac surgery during the last decades created the possibility of controlling vertigo. The results of inner ear surgery on hearing function have, however, not been fully satisfactory (Brackmann & Anderson, 1980; Thomsen et al., 1981). There has been an increasing need for new methods of improving the intralabyrinthine fluid pressure balance in order to influence the cochlear function.

Reports on inner ear dysfunction in connection with outside pressure changes indicate that external pressure conditions may influence inner ear function. Vestibular dysfunction has been described in connection with pressure changes during diving and flying (Lundgren, 1965; Tjernström, 1974). Vertigo and temporary shift in hearing thresholds have been reported after exposure to infrasound (Jerger et al., 1966; Nixon, 1973). Observations on the effects of rapid outside pressure changes and high levels of infrasound on the inner ear function in humans provided an incentive for research into inner ear hydrodynamics in relation to outside pressure changes. The inner ear pressure-regulating mechanisms were studied by the method involving direct measurement of the perilymphatic pressure (Carlborg et al., 1980). The transmission properties of various pressure changes were then investigated in detail (Densert et al., 1981). Knowledge on the transmission of other forms of pressure changes is,

however, necessary in order to better understand the relationship between the inner ear function and ambient pressure changes.

AIMS OF THE STUDY

The purpose of the present study was to explore the nature of the relationship between outside pressure changes and the inner ear hydrodynamics, and to investigate whether the inner ear function in Meniere's disease may be influenced by externally induced pressure changes.

The aims of the experimental part of the study were

- to investigate the transmission of square wave pressure pulses and overpressure complexes from the ear canal and the middle ear to the perilymphatic fluid,
- to evaluate what parameters of overpressure complexes produced an optimal positive pressure response in the perilymphatic fluid, and
- to describe the function of a pressure generator intended to induce pressure changes in the inner ear.

The aims of the clinical part of the study were

- to present a clinical method of quantifying psychoacoustical tuning curves (PTC),
- to investigate changes in frequency selectivity in patients with Meniere's disease, exposed to overpressure, and
- to investigate early effects of overpressure on cochlear function in patients with Meniere's disease.

EXPERIMENTAL PART

INTRODUCTION

Experimental studies on inner ear fluid pressures have been conducted by numerous investigators in order to gain a better understanding of the inner ear hydrodynamic processes (Kerth & Allen, 1963; Martinez, 1968; Beentjes, 1972). The behaviour of the inner ear fluid pressure was studied in response to exposure to pressure changes (McCabe & Wolsk, 1961; Parker & Reschke, 1972; Nedzelnitsky, 1974; Carlborg, 1981; Densert et al., 1981; Allen, 1983). The results from these experiments demonstrated a close hydrodynamic relationship between the inner ear fluid pressure and alterations in blood pressure, cerebrospinal fluid pressure and ambient pressure changes. Hyperosmotic substances were also found to have effects on the inner ear fluid pressure (Angelborg & Ågerup, 1975; Carlborg & Farmer, 1983).

Studies on the inner ear hydrodynamics in connection with Meniere's disease indicated that equal pressure on both sides of the cochlear partition, as well as a balance between endo- and perilymphatic fluid volumes, is required for normal functioning of the inner ear (Tonndorf, 1975; Allen, 1983). The possibility to elicit vertigo by applying local overpressure in the middle ear was demonstrated by Ingelstedt et al. (1974). The connection between inner ear symptoms in Meniere's disease and ambient pressure changes was first shown in patients with acute symptoms, using a pressure chamber (Densert et al., 1975; Ingelstedt et al., 1976). Exposure to overpressure aggravated the symptoms while the application of underpressure induced temporary relief of the symptoms.

The inner ear pressure-regulating mechanisms were investigated in animal experiments (Densert et al., 1981). The investigation disclosed some properties of the inner ear pressure transmission system in response to non-acoustical stimuli. It was found that the perilymphatic pressure levels could be affected more easily via middle-ear than ear-canal stimulation. An asymmetry in the response of the perilymphatic pressure to positive and negative pressure stimuli was found. In the majority of animals, positive pressure changes caused greater perilymphatic response and were less easy to stabilize than the corresponding levels of negative pressure changes. Sine pressure waves of infrasonic frequencies were found to cause a positive pressure shift in individuals with a positive asymmetry (Krukowski et al., 1980). It was also found that the process of pressure stabilisation was governed by two time constants, which were dependent on the patency of the cochlear aqueduct. The first phase of the perilymphatic fluid response

was then investigated. The second phase, which in response to a positive pressure application, always shows a negative pressure change in the perilymph, was not further analysed.

In order to analyse the effects of pressure applications on the inner ear fluid pressure, the relation between the amount of positive versus negative pressure change created in the perilymph should be more closely investigated.

Methods of direct measurement of the functional patency of the cochlear aqueduct in humans are not available. Morphological investigations on temporal bones from human adults show that the patency of the cochlear aqueduct may vary between individuals (Palva & Dammert, 1969; Rask-Andersen et al., 1977; Wlodyka, 1978). It is therefore important to investigate the function of the cochlear aqueduct in the stabilisation of different forms of pressure, before pressure parameters appropriate for influencing the inner ear fluid balance in humans may be proposed.

SUBJECTS AND METHODS

Papers I and II.

Experimental animals and general procedures

Fifteen cats weighing between 2 and 3.5 kg were used in the study.

The animals were anaesthetised by i.v. infusion of pento-barbital 30 mg/kg. All cats were provided with tracheotomy. The fluid balance was maintained by i.v. infusion of 5.5% glucose. The body temperature was kept constant by an electric blanket. Blood gases were monitored. The experimental investigation was approved by the Regional Committee of Ethics.

Surgical procedures

The perilymphatic pressure (Pp) was measured via an extra-aural approach into the vestibulum (Figure 1, Paper I). The skull bone was exposed and a conical canal drilled in a fronto-caudio-medial direction, cranially to the external ear canal. Care was taken not to damage the middle and inner ear structures, the facial nerve or to cause bleeding. A metallic canula (ID 0.8 mm) with a plastic adapter was fixed into the bony canal and sealed to prevent leakage of perilymph. A microtip pressure transducer was inserted into the adapter. The total volume of the pressure measurement system was about 12 mm³.

The ear canal was exposed via a retro-auricular incision for insertion of a rubber cuff with plastic tubes for application and measurement of pressure changes (Pec). A teflon tube was inserted through the tympanic membrane for application and measurement of middle ear pressure changes via the ear canal (Pm). Whenever pressure changes > 3 kPa were applied the Eustachian tube was blocked with epoxy resin in order to prevent leakage.

In order to block the cochlear aqueduct (CA), it was approached via an opening in the tympanic bulla. It was exposed under the operating microscope and blocked with amalgam. The opening in the bulla was closed with a rubber cuff, fitting exactly in the opening made in the bulla.

Experimental procedure

The following forms of pressure changes could be transmitted:

- Square wave pressure pulses with amplitudes within the range of 5 kPa.
- Low-frequency sine pressure waves of frequencies 5, 10 and 15 Hz and amplitudes from 0.5 to 3 kPa.
- Pressure complexes consisting of low-frequency sine pressure waves superimposed on static pressures. The amplitudes used were less than 4.5 kPa.

Square wave pressure pulses were applied to the middle ear

(P_m), via the ear canal, after insertion of a teflon tube into the tympanic membrane. The perilymphatic pressure (P_p) was measured continuously in the vestibulum during the experimental procedures.

Technical equipment

The pressures (P_m , P_p) were measured by microtip pressure transducers PC 360 6F (Millar Instruments INC., Houston, Texas, USA). The transducers were calibrated before each experiment and the pressure in the vestibulum was used as the reference zero.

The signals from the microtip transducers were processed in a specially built amplifier with a built-in calibration unit. The signals were recorded on an ink-jet recorder. Square wave pressure pulses were produced by a source of variable air pressure with manually operated valves (Paper I).

A pressure generator was specially constructed with two separate pumps for producing sine pressure waves and static pressure. The amplitudes of the pressures could be varied separately (Paper II).

RESULTS

TRANSMISSION OF SQUARE WAVE PRESSURE PULSES THROUGH THE PERILYMPHATIC FLUID IN CATS (I).

TRANSMISSION OF COMPLEX PRESSURE WAVES THROUGH THE PERILYMPHATIC FLUID IN CATS (II).

The perilymphatic pressure (P_p) was studied in response to square wave pressure pulses applied to the middle ear (P_m). A typical perilymphatic response to a middle ear stimulus in a cat with a patent cochlear aqueduct (CA) is shown in Figure 2 (Paper I). It was found that each pressure change gave a double-phased response in the perilymphatic fluid. The initial pressure response occurred instantly upon application of the stimulus and the second, rebound phase, appeared upon the cessation of the pressure stimulus. In most cases two time constants could be found in both the initial and the rebound phase of the perilymphatic pressure response. Analysis of the values of the time constants calculated from the pressure stabilisation curve showed that the time constants for the positive pressure stimuli were longer than the corresponding time constants for the negative pressure inputs. The values of the time constants are presented in Table I (Paper I).

The integrated areas of the positive pressure change and the negative pressure change, corresponding to the initial and the rebound perilymphatic pressure response, respectively, were calculated. In response to square wave pressure pulses, the ratio of the positive versus negative pressure change varied from 0.8 to 1.3 and was not influenced by the amplitude or duration of the input signal. After the CA was surgically blocked, the pattern of pressure stabilization was greatly changed as shown in Figure 5 (Paper I). The two time constants, earlier observed in the initial perilymphatic response, disappeared and one almost infinitely long time constant was recorded. The rebound pressure response disappeared nearly completely, indicating that no perilymphatic fluid was being transmitted through the CA during the pressure application. This was valid for both positive and negative pressure signals. Since the rebound pressure response became insignificant after the CA was blocked, the ratio of the positive/negative pressure change was increased and found to be proportional to the amplitude and the duration of the input signal.

Complex pressure stimuli were transmitted through the middle ear, via a teflon tube inserted into the tympanic membrane. Table I (Paper II) shows that the time constants, calculated from the perilymphatic pressure curve in response to the pressure complexes, were increased compared with those elicited with square wave pressure pulses. The ratios of the positive and negative pressure changes in the perilymph i.e. integrated positive pressure change (IPPC) versus integrated negative pressure change (INPC), were calculated for four

different types of pressure complexes. The results are illustrated in Figure 3 (Paper II). The results indicated that the highest ratio was obtained when applied pressure complexes had amplitudes < 2 kP and a time duration < 3 s. However, there were individual differences in regard to the ratio obtained in response to the pressure complexes. These differences were shown to be dependent on the patency of the CA. In individuals with a low patency of the CA, the pressure ratio was considerably higher. When the CA was experimentally blocked, similar results for the ratio were obtained, independent of whether square wave pressure pulses or pressure complexes were applied. No significant difference was found in the results by changing the frequency of the sine pressure waves between 5 and 15 Hz.

CONCLUSIONS

The use of pressure changes of a complex nature seems to influence the rate of the inner ear pressure stabilization process, as indicated by the values of the time constants, which appeared to be longer in response to pressure complexes than to square wave pressure pulses of corresponding levels.

The results suggest that the use of complex pressure changes will influence the functional patency of the CA in such a way that the inner ear hydrodynamic system exhibits an increased impedance in response to such pressure stimuli.

Using complex pressure changes, a prevailing positive pressure change may be obtained in most individuals with an open CA. It may be concluded that the inner ear pressure-regulating system in cats is mainly governed by the patency of the CA. The perilymphatic pressure stabilisation can, however, be influenced by varying certain pressure parameters.

CLINICAL PART

INTRODUCTION

The hearing loss in Meniere's disease displays characteristic features of cochlear impairment - equal elevation of hearing thresholds for air and bone conduction, recruitment, harmonic distortion and loss of speech intelligibility. According to the results of morphological investigations and animal experiments, fluctuations in hearing impairment are considered to be directly related to a disturbance in the inner ear hydrodynamics (McCabe & Wolsk, 1961; Schuknecht, 1963; Kimura & Schuknecht, 1965).

Tonndorf's (1975) experiments on cochlear models have partly clarified the mechanisms of different components of the sensorineural hearing loss in Meniere's disease. Elevation of hearing thresholds in pure tone audiometry was considered to be due to an increase in mass of the cochlear partition. Distortion phenomena and a subsequent loss of speech intelligibility were attributed to a change in dynamic properties of the cochlear partition and biasing of the basilar membrane loaded by hydrops. Flottorp's (1980) investigations on aural harmonic thresholds and loudness summation showed that the hearing function in patients with Meniere's disease was influenced by elements of distortion presumably due to a loss of elasticity of the inner ear membranes.

Hearing measurements performed with conventional audiological tests do not provide an adequate description of the single functional unit of the cochlea since sensitivity to sound cannot be distinguished from the function of sound analysis by means of pure tone or speech audiometry.

The ability to distinguish between two different sounds, on the basis of frequency, which are presented simultaneously, is referred to as frequency selectivity (Møller, 1983). Psychoacoustical tuning curve (PTC) measurements are considered to be analogues to neurophysiological frequency tuning (Kiang, 1965).

The psychoacoustic methods of obtaining PTC's in humans are relatively new and the results of different techniques have been difficult to interpret. It is though agreed that the shape and position of the tip of the curve give an indication of the damage to the inner ear. Sharply tuned tips of PTC's have been associated with good frequency selectivity, while broadened curves have been obtained in subjects with a sensorineural hearing impairment (Florentine et al., 1980). The frequency selectivity may be estimated either from the

general shape of the PTC or by means of the Q_{10} value, which describes the width of the auditory filter 10 dB above the test tone level. More exact methods to measure quantitatively changes in the shape of PTC's have not been available. In order to evaluate the amount of change in frequency selectivity, in patients with Meniere's disease and in relation to overpressure, it was necessary to develop a method of quantifying the PTC's.

To test the hypothesis that the hydrodynamic properties of the cochlea in Meniere's disease may be influenced by outside pressure changes, studies were conducted on the cochlear function in a number of patients with varying degrees of sensorineural hearing impairment.

SUBJECTS AND METHODS

Paper III deals with 20 subjects, divided into two groups. The first group consisted of 10 normal-hearing subjects (hearing thresholds within 10 dB re. ISO 389 1975), 20 to 30 years old. The second group consisted of 10 subjects with Meniere's disease, 40 to 50 years old, with hearing levels between 50 and 65 dB PTA.

Paper IV deals with 14 other patients with diagnosed Meniere's disease (average age of 50 years). Their hearing levels were between 45 and 65 dB PTA. The patients did not receive any treatment for at least 6 months prior to the start of overpressure exposure. The period of exposure to overpressure was predetermined and limited to 4 months.

Paper V comprises 19 patients with Meniere's disease. Fourteen of these are the same as reported in Paper IV. The other 5 showed hearing losses > 70 dB PTA (70 - 85 dB PTA). The period of exposure to overpressure was extended to 12 months.

The diagnosis of Meniere's disease was based on history, medical examination and audiological findings. The glycerol test and caloric test were performed. X-ray examination was made to exclude malformations or tumors affecting the temporal bone.

Technical equipment

The technical set-up used to obtain the psychoacoustic tuning curves (PTC's) included a Madsen OB 70 pure tone generator which was used for the emission of the test tone. A specially built pure tone generator was used to produce six different masker frequencies, close to the frequency of the test tone. A Danplex AS 72 audiometer provided a narrow-band noise for masking of the contralateral ear. A microcomputer, IBM PC (IBM Corp. CA, USA), was used for calculations and storing of the PTC data.

A specially constructed pressure generator (described in Paper II) emitted pressure changes with the required parameters.

Audiological tests

Pure tone audiometry and speech discrimination tests were performed repeatedly on all patients.

Psychoacoustic tuning curves were obtained by a simultaneous masking technique. The PTC testing technique is described in detail in Paper III.

Computational procedures

In order to analyse the function of the PTC the curve was split into two parts. The masker frequencies less than the test frequency were analysed as the tail part, and the masker frequencies larger than the test frequency as the steep part.

The f/f_0 value of the test tone was then 1.0. The following transformation of the f/f_0 variable was made

for tail $x' = 100(1 - f/f_0)$

for steep $x' = 100(f/f_0 - 1)$

x' representing the relative distance in frequency between masker and test tones.

In order to estimate the slopes (k) of both parts of the curve, the data points of the tail and steep part were fitted, using the method of linear regression. The three data points from the tail and the three data points of the steep part of the curve are illustrated in Figure 1 (Paper III). In order to describe the parameter value of the test tone a third parameter (H) was introduced. H was defined as the vertical distance between the test tone level and a straight line joining the extreme points of the PTC. The properties of the PTC function were thus described by three parameters - k (tail), k (steep) and H (height). The method of calculation of the three parameters of the curve is illustrated in Figure 1. (Paper III).

In this way data were obtained describing the PTC function in normal-hearing subjects. The data obtained from the hearing-impaired subjects were transformed in the same manner. It was then possible to make a quantitative evaluation of the inner ear frequency selectivity in individual patients in relation to normal-hearing subjects. In order to facilitate this evaluation a system of scores was designed which is described in detail in Paper III.

The data on frequency selectivity was obtained in normal-hearing and hearing-impaired subjects by means of test-retest procedure in order to study the reproducibility of the tests and to estimate the variations in the results due to the method of testing.

Statistical evaluations were carried out using the t-test, the Wilcoxon test for paired observations, and the tests for correlations (Papers III, IV and V).

Pressure application procedure

Pressure applications were administered from the pressure generator into the ear canal by means of a short polyethylene tube. The pressure changes were then transmitted to the middle ear via a transmyringial teflon tube (Paper IV).

The pressure applications consisted of pressure complexes where sine pressure waves were superimposed on a static pressure. The total amplitude was < 3.5 kPa. The static pressure level component was kept below 1 kPa. The duration of the pressure applications was varied individually and was always less than 3 s. The intensity and frequency of pressure applications were individually scheduled for each patient. The period of pressure exposure was generally four months but was for some patients extended to 12 months (Paper IV and V).

RESULTS

QUANTIFYING PSYCHOACOUSTIC TUNING CURVES FOR CLINICAL USE (III).

The information contained in the PTC's was transformed by means of mathematical computation into a scoring system. The operation is described in detail in the paper. This model allowed evaluation of the frequency selectivity in relation to that obtained from normal-hearing subjects.

Generally, the PTC's obtained from subjects with a cochlear impairment, due to Meniere's disease, were broader and shallower, while the PTC's from the normal-hearing subjects were sharply tuned. In Figure 3 variations between hearing-impaired subjects are shown. The figure illustrates also how the scoring system reflects the frequency selectivity in these subjects.

All the PTC data were obtained by the test-retest procedure in both normal-hearing and hearing-impaired subjects. For the purpose of the present investigation it was important to be able to estimate quantitatively variations in inner ear frequency selectivity dependent on the the method of measurement. Based on test-retest calculations, it was inferred that variations larger than 8 to 10 units might be attributed to a change in the frequency selectivity at the 95 % confidence level.

EFFECTS OF OVERPRESSURE ON HEARING FUNCTION IN MENIERE'S DISEASE (IV).

Results on hearing function in relation to overpressure exposure in patients with Meniere's disease are presented in Table I. The table comprises hearing parameter data from 14 patients. None of the patients showed signs of deterioration in hearing. Statistically significant improvement was found in all hearing parameters. The Wilcoxon test gave $p < 0.001$.

The use of PTC's allowed spatial observations of changes in inner ear frequency selectivity during the period of overpressure exposure. Figures 3 and 4 show changes in PTC shapes at test frequencies of 500 and 2 000 Hz in two different patients. The change in frequency selectivity was less pronounced at 2 000 Hz. Corresponding improvements in hearing threshold levels are also shown.

AIR-BONE GAP IN MENIERE'S DISEASE AFTER EXPOSURE TO OVERPRESSURE (V).

An air-bone gap was disclosed in 16 out of 19 patients during overpressure exposure. It was shown that the occurrence of an air-bone gap could be correlated to an increase in speech

discrimination scores. This was also accompanied by an improvement in the PTC's. Air-bone gaps and corresponding changes in hearing threshold levels and PTC's are shown in Figures 1 and 2 for two different patients. Table I comprises changes in hearing parameters in all the patients.

METHODOLOGICAL CONSIDERATIONS

Perilymphatic pressure measurements

The direct method of measurement of the perilymphatic pressure, used in this study, has been tested previously under experimental conditions (Carlborg et al., 1980). Several technical and methodological advantages were the reason for choosing the method in this investigation. The operating procedure of gaining access into the vestibulum via a canal drilled in the skull and temporal bone, and of surgical blockage of the cochlear aqueduct might constitute considerable technical problems. However, these operating techniques have been accomplished previously by the authors in numerous animal experiments and could therefore safely be used without creating damage to the middle ear, facial nerve, semicircular canals or the intracranial cavity.

A single experiment required stable conditions in the experimental animal and stable performance of the technical equipment for as long as ten hours. The characteristics of the microtip pressure transducers allowed continuous recordings for long periods of time. This type of transducer was suitable for these measurements in small cavities with a total volume of the pressure measurement system of about 12 mm³ and a small volume displacement.

Calculation of the time constants of the perilymphatic pressure response was performed. The method of calculation used in this study was somewhat different from that employed by Densert et al. (1981), and allowed greater accuracy. Log (Pp) of the perilymphatic pressure response curve was plotted as a function of time. The time constants could thus be identified. The values of the time constants were calculated as shown in Figure 3 & 4 (Paper I), using the equation

$$\tau = \frac{t_{1/2} - t_1}{\ln 2} \quad (\ln 2 = 0.693)$$

Psychoacoustic tuning curve measurements

The influence of outside pressure changes on the inner ear function in Meniere's disease has been a central issue in this work. The criteria of the American Academy of Ophthalmology and Otolaryngology Committee on Equilibrium (Alford, 1972) allowed differentiation between an improvement and non-improvement in pure tone audiometry and an absence or recurrence of vertigo. For the purpose of our investigation this system of evaluation was not considered sufficient since a more detailed analysis of the hearing function was required.

Pure tone audiometry measures only the sensitivity levels for pure tones, and speech discrimination tests involve different levels of auditory processing. Different psychoacoustic techniques, such as measurement of the critical band, two-tone suppression and PTC measurements are known. It is, however, considered that PTC's most closely describe the frequency selectivity of the inner ear (Zwicker & Schorn, 1978; Florentine et al., 1980).

Various psychoacoustic techniques have been used to obtain PTC's. PTC's obtained by a simultaneous masking technique have been considered representative for the basic frequency tuning of the basilar membrane (Houtgast, 1973; Moller, 1983). It was therefore considered adequate as a tool in the evaluation of changes in cochlear function. Although it has been shown that PTC's obtained by means of a forward masking technique are more sharply tuned, the technique of simultaneous masking was applied in this study. PTC's obtained with this technique have been considered easier to interpret since the forward masking technique involve other tuning mechanisms (Moore, 1978, 1982). For our purpose a simplified method of PTC measurement was chosen (Zwicker & Schorn, 1978).

The testing of frequency selectivity in hearing-impaired subjects raised considerable problems. Unilateral hearing impairment involved the necessity of masking the opposite ear. Such masking increased the level of difficulty of the testing procedure, particularly in patients with tinnitus and recruitment. The problem of central masking also arose. The question of whether to compensate for the effects of central masking, as the hearing thresholds improved, has been discussed. It was agreed that the influence of central masking on the shape of the PTC's could be considered negligible (Zwicker, personal communication).

In order to ensure reliability of the PTC tests all subjects were trained in the testing technique before the collection of the data. The basic PTC data were obtained in test-retest procedures. In hearing-impaired subjects combination tones may appear when the sensorineural hearing loss exceeds 55 dB PTA (Zwicker & Schorn, 1978). It is thus necessary that results from patients with such advanced hearing loss should be interpreted with caution. In our investigation, the patients could usually give reproducible results when the sensorineural hearing loss was < 65 dB PTA. Patients with greater hearing loss often reported the occurrence of interference tones and were unable to reproduce the test results.

Quantifying PTC's

PTC's have previously been analysed quantitatively in terms of an auditory filter (Zwicker, 1974; Patterson, 1976). The width of the curve, measured above the test frequency has been used as a common parameter in comparing data from different measurement techniques. Using this evaluation method, the assumption had to be made that the function of the auditory

filter was symmetric and linear. In the present work an attempt was made to more fully describe the PTC function and to see whether a change in frequency selectivity could be evaluated more closely. To meet this purpose, information contained in the PTC was analysed by means of a curve-fitting technique. The shape of the curve suggested that it could be represented by two different functions. The curve therefore was split into two parts and the "tail" and "steep" functions were analysed separately. The mathematical transformation of the x-scale enabled data fitting of the points on each side of the test tone. Curve fitting was performed using linear regression.

In order to facilitate the quantitative evaluation of the inner ear selectivity a system of scoring was designed based on the PTC parameters obtained from a group of normal-hearing subjects. The slopes of the tail part, k_t , and the steep part, k_s , were considered to be closely correlated to the frequency selectivity. These two parameters were considered equally important. The third parameter H (height), was introduced as a measure of the test tone level in relation to the masker levels at the extreme points of the abscissa. Testing the model on normal-hearing and hearing-impaired subjects, it was observed that when equal importance was attributed to these three parameters, the total score value was overestimated in subjects with poor frequency selectivity. The parameter H was therefore weighted by a factor of 0.5 in order to reduce its influence on the total score. It should be emphasized that the scores do not express absolute values of the frequency selectivity but may serve as an easy tool for making estimates of a given PTC in relation to "normal" frequency selectivity. The scores ranged from 0 to 100. A flat PTC gave a score of 0 while a "normal" PTC function gave a score of 100. Negative score values could be obtained in cases with an inverted peak or descending slopes.

In order to evaluate whether changes in frequency selectivity could be considered significant it was necessary to estimate the variations in the PTC that could be attributed to the method of testing. The test-retest procedure was therefore performed in all normal-hearing and hearing-impaired subjects included in the study (Paper III). Data obtained from the test-retests were then analysed in terms of scores. Using the t-test, evaluation of the reproducibility of the PTC tests and of the amount of variations in scores dependent on the method of testing, were made (Paper III).

The absolute values of the PTC parameters (in dB and dB SPL) were made accessible through the computer program, which allowed storing of the basic frequency tuning data.

GENERAL DISCUSSION

Changes in production, reabsorption and circulation of the endolymphatic fluid, leading to an increase of the endolymphatic volume, are considered to be responsible for the inner ear symptoms in Meniere's disease (Hallpike & Cairns, 1938; Lindsay, 1946; Schuknecht, 1963). Management of the inner ear symptoms therefore is aimed at a reduction of the endolymphatic volume (Arenberg et al., 1983; Shea, 1983). It is, however, still debatable whether the inner ear hydrodynamics may be influenced by current methods of treatment (Thomsen et al., 1981; Allen, 1983).

The connection observed between ambient pressure changes and inner ear function indicated a new way of influencing the inner ear function (Lundgren, 1965; Jerger et al., 1966; Nixon, 1973; Ingelstedt et al., 1974). The first attempts to control the symptoms in Meniere's disease by ambient pressure changes were made when patients with acute symptoms were exposed to pressure changes in a pressure chamber (Densert et al., 1975). The patients improved in response to underpressure and their hearing deteriorated when overpressure was applied in the pressure chamber. This pointed to a relationship between the inner ear function in Meniere's disease and external pressure changes. It has been presumed that since the inner ear fluids are incompressible, the induction of a positive pressure change in the inner ear may reduce the endolymphatic fluid via the inner ear pressure communication routes (Densert & Densert, 1982). An improvement in the inner ear symptoms may then be expected. The induction of a negative pressure change in the inner ear may, on the other hand, induce further expansion of the endolymphatic compartment and aggravate the symptoms. Experimental and clinical results obtained in this study may shed some light on the validity of this hypothesis.

In the experimental part of this work, conditions for the inducement of a positive pressure change to the inner ear fluids have been investigated. It was shown that the inducement of a positive pressure change was primarily dependent on the patency of the cochlear aqueduct (CA). The rate of the inner ear pressure stabilisation in each cat may be described by means of time constants, characteristic for each cat. In animals with a closed CA, transmission of positive square wave pressure pulses or complex pressure changes, gave almost an exclusively positive perilymphatic pressure response. The problem of inducing an intralabyrinthine positive pressure change appeared more complex in cases with an open CA. The ratio between a positive and a negative perilymphatic pressure response was close to 1 when square wave pressure pulses were applied. The use of complex pressure changes seemed to change

the pattern of perilymphatic pressure response by influencing the values of the time constants.

An increase in the values of the time constants obtained from animals with an open CA, exposed to complex pressure changes, indicates that the inner ear hydrodynamic system responds to pressure complexes with an increased impedance. The decrease in rate of perilymphatic pressure stabilisation suggests a partial, functional blockage of the CA.

In his experimental study, Allen (1983) postulates that a relatively large pressure increase (> 10 cm Hg) is needed to influence the volume/pressure relations of the endo- and perilymphatic fluids. In Allen's work the effects of prolonged hydrostatic pressures were discussed. The pressure changes were applied in the cerebrospinal fluid and their effects may not be comparable to the effects of complex pressure changes, applied via the middle ear. In our experience bleedings and ruptures may occur in the inner ear at input levels > 4 kP. By varying the pressure input parameters, it was found that the optimal ratio of positive to negative pressure change in the inner ear fluids was obtained for relatively low pressure levels and short pulse durations. The exchange of the inner ear fluids operates at the capillary level, where the effective filtration pressure is low (Rauch, 1968). Low input pressure levels may thus prove sufficient for the displacement of endolymphatic fluid.

Since the inner ear hydrodynamic system cannot be directly studied in humans, knowledge of the same system in cats has, with some reservations, been applied in the clinical part of this investigation. However there are anatomical similarities in the organ of Corti between these two species, the question of functional patency of the CA in human adults still remains unclear. While most investigators claim that the CA in human adults is generally not patent (Rask-Andersen et al., 1977), the majority of our patients with Meniere's disease respond more favourably to complex pressure changes than to applications of square wave pressure pulses. This observation would indicate that in most patients, the CA is still functionally patent.

In the clinical part of this work the hypothesis was put forward that the hearing function in Meniere's disease could be influenced by means of external pressure applications. Besides classical audiological tests, PTC's have been used to evaluate changes in the cochlear function. PTC's, describing the basilar membrane frequency resolution pattern, have been chosen to serve as a sensitive measure of changes in hearing function. In patients with advanced hearing loss, gradual changes in the shape of the PTC were observed during exposure to pressure applications. From an almost complete dissolution in shape, the PTC improved to show distinctive tail, steep and tip parts.

Previous methods of evaluating the PTC's allowed a general

assessment of the shape of the curve (Florentine et al., 1980; Pickles, 1982). PTC's have also been analysed in terms of an auditory filter. Measurements of the Q 10 value have been particularly useful in evaluating PTC's obtained from normal-hearing subjects (Moore, 1982). PTC's obtained from patients with advanced sensorineural hearing loss are often so distorted that it is difficult to identify the Q 10 values. In the curve fitting model, presented in this work, the three parameters were used to describe the PTC's. The data were derived from young normal-hearing subjects and the "normal" highest score was set at 100. Due to individual variations, the curves from some normal-hearing subjects were more sharply tuned, than the "normal" curve, obtained from the averaged PTC data. The total score values of such curves exceeded 100 score units. On the other hand, in hearing-impaired subjects, negative total score values could be found, due to distorted forms of the curves, with reversed directions of the slopes or the tip.

The system of scoring seems thus to reflect variations in frequency selectivity, found in normal-hearing and hearing-impaired subjects. In a number of patients with Meniere's disease with well defined hearing loss (Paper IV) the PTC scores showed significant improvement together with an increase in speech discrimination during exposure to pressure applications. In some patients only a slight change was observed in pure tone levels, although the PTC and speech discrimination scores showed significant improvement. In other patients, despite nearly complete restoration of hearing levels, the PTC did not give a maximum score. The data used to quantify the PTC's were derived from young, normal-hearing subjects, while the average age of the patients in our study was about 50 years. The age-dependent differences in frequency selectivity are to be studied further.

The observation of an air-bone gap in Meniere's disease has been made by Goodhill & Harris (1979). Its significance has remained obscure because of the uncertainties associated with measurements of bone-conduction thresholds (Barány, 1938; Carhart, 1950). In the present work the appearance of air-bone gaps was often associated with changes in the quality of hearing and a reduced feeling of fullness in the ear. It was also related to changes in speech discrimination and PTC scores. The transformation of a sensorineural hearing loss to that with a conductive component may be attributed to an improvement in the hydrodynamic properties of the cochlea. Since no significant change could be found in the stapedius reflex thresholds after the appearance of the gaps, the conductive component could presumably be localized to structures beyond the stapes footplate and caused by an increased mass of the endolymphatic fluid. As the hearing function further improved, the relative differences in air- and bone-conduction thresholds decreased in most patients, causing a decrease or disappearance of the air-bone gap. The air-bone gap described here can thus be seen as a transient phenomenon reflecting dynamic changes in the inner ear exposed

to pressure applications.

The present results give indications of quantitative and qualitative changes in hearing function in a number of patients after exposure to pressure changes. Establishing the cause/effect relation in Meniere's disease has always been difficult because of the fluctuating course of the disease. It has also been suggested that a placebo may have an effect on the symptoms, particularly on fullness and vertigo. In the present study the technique of pressure application involved repeated calibrations of pressure levels. For these reasons an open study was chosen. Only the hearing function was studied since no certain effects have so far been established on this parameter, either in connection with different treatment methods, or placebo (Thomsen et al., 1981).

According to biostatic investigations, the validity of inference from open studies (Bailar et al., 1984) may be strengthened by other important features, such as explicit definition of hypothesis and thorough exploration of serial data measurements. In the present study, the clinical hypothesis was formulated a priori and the study focused on the hearing parameters. The methods of measurement of the clinical variables have been chosen to reflect presumptive changes in inner ear function as a result of the exposure to overpressure. Non-parametric and parametric tests, allowing the use of relatively small samples have been used for testing the significance of these changes. Provided that the results from these tests are strictly applicable to the set of hypotheses formed in this study, the information obtained may serve as a field test in the search for methods of symptom management in Meniere's disease.

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Transmission of Square Wave Pressure Pulses through the Perilymphatic Fluid in Cats

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The inner ear hydrodynamics have been studied in a series of experiments on cats. A detailed analysis has been made of the perilymphatic pressure response to square wave pressure pulses applied to the ear canal and middle ear. It was found that the initial pressure response was followed by a rebound pressure response of the opposite phase. It was also found that in most cases each phase of the pressure response could be expressed in terms of two time constants. When the cochlear aqueduct was patent, the perilymphatic pressure response showed almost equal positive and negative pressure changes. However, when the cochlear aqueduct was surgically blocked, the perilymphatic pressure response consisted almost exclusively of the first phase of the response, while the rebound phase disappeared almost completely. The possibility of influencing the inner ear fluid balance in Meniere's disease by external pressure changes is discussed in the light of the present experimental results. *Key words: Meniere, inner ear hydrodynamics*

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Morphological studies on temporal bones from patients with Meniere's disease indicate that inner ear symptoms may be directly related to a distension of the endolymphatic system (1, 2, 3). Different forms of decompression of the endolymphatic compartment have therefore been tried in attempts to restore the intralabyrinthine pressure balance and alleviate inner ear symptoms (4, 5, 6, 7).

A relationship between ambient pressure changes and inner ear disorders has been reported by several authors (8, 9). Evans (10) has also reported a relationship between infrasound exposure and inner ear symptoms. However, the hydrodynamic mechanism governing this relationship is poorly understood. Effects on the acute symptoms of Meniere's disease from relative over- (increased) and underpressure (decreased) in a pressure chamber indicated the possibility of influencing inner ear hydrodynamics by means of pressure changes (11). In a number of patients with advanced Meniere's disease, overpressure pulses were applied in the middle ear. The results of this pilot study indicated that it may be possible to improve the inner ear function by means of overpressure stimulation (12).

Studies on the hydrodynamics of the inner ear in humans are, however, difficult to perform because of the vulnerability of the system. Animal experiments and studies on cochlear models have therefore been performed to clarify the relationship between pressure changes in the perilymphatic and endolymphatic systems (13, 14, 15, 16).

In order to better understand the nature of the relationship between pressure changes in the perilymphatic system and ambient pressure changes, we performed series of experiments on cats. Experiments on the transmission of pressure changes from the ear canal and the middle ear to the inner ear fluids gave information on the inner ear pressure regulating mechanisms (17). It was found that pressure changes were transmitted to the inner ear

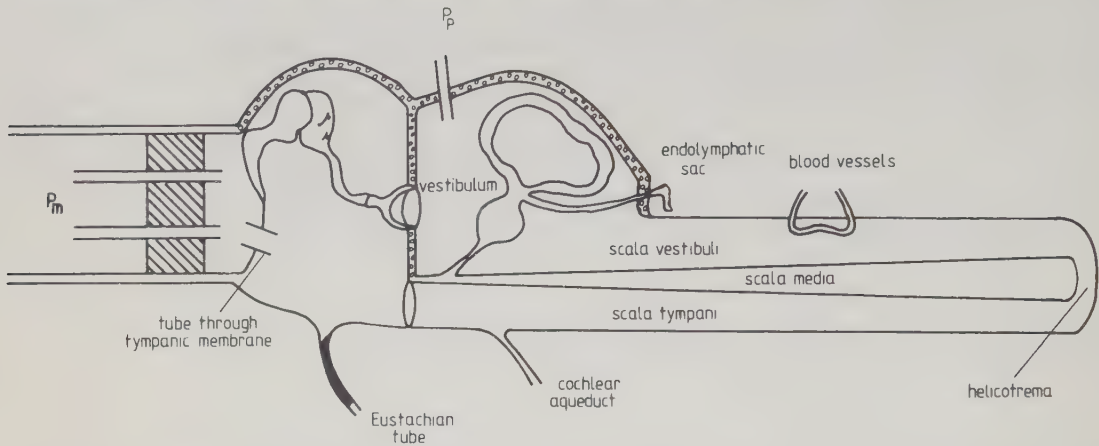


Fig. 1. Cross-section of the ear showing the points of access used in the experiments. P_p , perilymphatic pressure; P_m , middle ear pressure.

fluids instantaneously, and that the perilymphatic pressure response had a larger amplitude when positive pressure changes were applied than when negative pressure changes were applied.

Each pressure change in the inner ear fluids was compensated for according to an individual pattern. Thus, the process of pressure regulation is thought to occur via different pressure release routes. It was demonstrated that the cochlear aqueduct generally had the greatest pressure releasing capacity.

For the development of a new method of management of inner ear symptoms in Meniere's disease, further investigations into the relation between inner ear hydrodynamics and external pressure changes are needed.

The aims of this study were therefore:

- to investigate the time pattern of the pressure response of the perilymphatic fluid to rapid square-wave pressure pulses transmitted from the middle ear to the inner ear fluids;
- to evaluate the amount of positive versus negative pressure response in relation to a square-wave stimulus, and
- to evaluate the amount of positive and negative pressure response as a function of the patency of the cochlear aqueduct.

SUBJECTS AND METHODS

Fifteen cats weighing between 2.5 and 3.5 kg were used. Full-length experiments could be performed on 10 cats. They were anaesthetized with intravenous pentobarbital and tracheotomized. The animals breathed spontaneously or were ventilated with a respirator. The blood gases were monitored during the experiments. A 5.5% glucose solution was infused intravenously and the body temperature was kept constant at 36°–38°C by means of an electric blanket.

Using a source of variable air pressure, single square-wave pressure pulses were applied to the middle ear. The points of access are shown in Fig. 1. The amplitude of the pulses could be varied from 0 to 5 kPa. When pressures exceeding 3 kPa were used, the Eustachian tube was blocked with epoxy resin in order to prevent leakage. Pressures exceeding 4.5 kPa were not used as these can cause damage to the middle and inner ear structures.

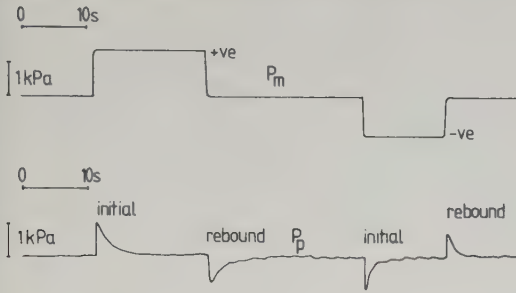


Fig. 2. Typical perilymphatic pressure response P_p to positive and negative input pressure applied to the middle ear (P_m) with a patent cochlear aqueduct.

Earlier experiments have shown that when pressure was applied to the middle ear via (17), the features of the perilymphatic pressure response were, in general, the same as those resulting from the application to the middle ear via a transmyringal drainage tube, in the tympanic membrane. Therefore, middle ear pressures could be applied and measured via polyethylene tubes fitted into a rubber stopper that was inserted and sealed in the ear canal, as shown in Fig. 1.

The perilymphatic pressure (P_p) was measured in the vestibulum. In order to do this a metallic cannula with an inner diameter of 0.8 mm was fitted and sealed in a canal opened up by approaching the inner ear from behind the auricle. The canal was drilled in the frontomedial direction cranially to the ear canal. Care was taken not to damage the adjacent middle and inner ear structures.

For measurements of pressure changes in the vestibulum and middle ear, Millar microtip PC 350 5F pressure transducers were used (Houston, Texas). The signals from the transducers were transmitted and processed in a specially designed amplifier with a low noise level and a built-in calibration system.

Via an opening made in the bulla, the cochlear aqueduct was approached and blocked. The cochlear aqueduct was exposed by drilling posteriorly and medially to the round window, and was then transected and blocked with amalgam. The opening made in the bulla was then sealed and middle ear pressure changes could be applied. Continuous measurements of the perilymphatic pressure were performed before, during and after the transection and blockage of the cochlear aqueduct. For details of the method, see Carlborg et al. (18).

Calculation of the time constants of the perilymphatic pressure response curve

Fig. 2 shows a typical perilymphatic fluid pressure response recorded in the vestibulum to positive and negative pressures applied to the middle ear via a tube through the tympanic membrane. The form of the perilymphatic pressure response suggested that one or more time constants may be involved in the inner ear pressure stabilization process. Therefore, $\log(P_p)$ was plotted as a function of time, (Fig. 3), thus enabling the time constants to be evaluated.

The time constants were calculated as shown in Fig. 4. A value, P_1 , of P_p was chosen ($P_1 < P_{\max}$) and the corresponding time, t_1 was read off. The value of $P_{1/2}$ was found ($P_{1/2} = P_1/2$) and the corresponding time $t_{1/2}$ was read off. The time constant, τ , is then given by:

$$\tau = \frac{t_{1/2} - t_1}{\ln 2} \quad (\ln 2 = 0.693)$$

In other words, the steeper the curve, the shorter the time constant.

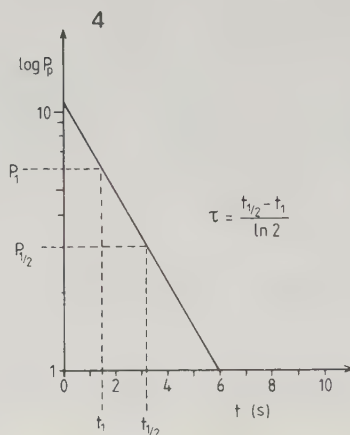
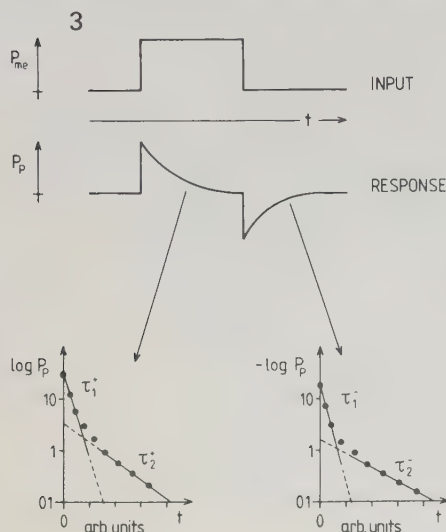


Fig. 3. Extraction of data points for the calculation of time constants. (For details, see main text.)

Fig. 4. Method of calculation of the time constants. (For details, see main text.)

Integration of positive and negative perilymphatic pressure response

In order to evaluate the extent of positive and negative pressure change in response to a single pressure application, the areas above and below the initial perilymphatic pressure level were calculated using a computer. The spatial resolution was 0.1 mm and the results are given in mm².

RESULTS

Each pressure change applied to the middle ear resulted in a double-phased response in the perilymphatic fluid (Fig. 2). The first phase is referred to as the 'initial response' of the perilymphatic fluid and it appeared instantaneously upon the application of the stimulus. After its initial peak, the perilymphatic pressure was seen to return to its initial level in a manner which was specific for each cat.

The second phase of the perilymphatic fluid response also occurred instantaneously upon the cessation of the pressure stimulus. This second phase in the response is a direct reaction to the cessation of the stimulus, and is referred to as the 'rebound response'. The rebound pressure also returned to the initial perilymphatic pressure in a time and manner specific for each cat.

A positive pressure application resulted in a positive initial pressure response followed by a negative rebound response (see Fig. 2). The magnitude of the rebound pressure response peak (P_{p2}) was, in nearly all cases, smaller than that of the initial pressure response peak (P_{p1}) although both responses were initiated by the same change in external pressure. When positive and negative pressure changes of the same magnitude were applied, the initial response peak was not always of the same magnitude in the two cases.

In most cases two time constants could be calculated in both the initial and rebound pressure responses. The results for 10 cats are summarized in Table I where the average

values of the time constants for each cat are given. The superscripts + and - refer to positive and negative P_p , respectively, regardless of whether the stimulus was positive or negative, and the subscripts 1 and 2 refer to the shorter and longer time constants of each response curve, respectively. Although the standard deviations are large, it is evident that the time constants for positive pressure stimuli are longer than for negative stimuli. This trend is confirmed when paired samples for each cat are compared. In 2 cats (9 & 10) an unusually slow pattern of pressure stabilization, giving very long time constants, was observed. In these two cases, the time constants were especially long for positive pressure stimuli.

Calculations of the ratio of the area of the initial perilymphatic response to the area of the rebound pressure response gave values approximately equal to 1 (0.8–1.3). This ratio was not significantly influenced by increased input levels or duration of the pressure application. The results for cats 1 to 8 are presented in Table II where the average values of the area ratios are given for each cat. For cats 9 and 10 the ratios were considerably larger.

After the clackage of the cochlear aqueduct both the initial and the rebound pressure response were changed, as can be seen in Fig. 5. The two time constants earlier observed in the decay of the initial pressure response disappeared and one almost infinitely long time constant was recorded. In the cases of both positive and negative input pressure, the rebound response disappeared almost completely and only a slight change was observed in

Table I. *Mean values of time constants for each cat for positive (+ve) and negative (-ve) input pulses applied to the middle ear*

The results for cats 9 and 10 have not been included in the mean values because of the very long time constants obtained

Cat	Input	τ_1^+ (s)	τ_2^+ (s)	τ_1^- (s)	τ_2^- (s)
1	+ve	4.3	6.5	4.0	11.0
	-ve	2.3	4.4	2.0	5.1
2	+ve	10.5	—	8.6	29.0
	-ve	6.8	—	4.3	11.8
3	+ve	2.2	5.7	2.7	4.0
	-ve	—	—	—	—
4	+ve	0.5	1.3	0.6	1.2
	-ve	0.6	1.4	0.2	1.1
5	+ve	1.8	—	2.5	4.9
	-ve	1.2	2.7	0.8	3.8
6	+ve	4.0	5.8	2.7	11.3
	-ve	1.3	3.2	0.8	9.7
7	+ve	2.7	9.0	3.9	15.5
	-ve	1.0	5.1	1.2	9.6
8	+ve	0.8	3.1	0.7	2.4
	-ve	0.4	1.7	0.5	1.7
9	+ve	14.7	37.7	7.7	>214
	-ve	4.0	114	4.2	41.4
10	+ve	29.2	28.8	2.0	28.9
	-ve	0.8	20.1	1.9	14.5
Mean		3.3±3.2	5.1±2.5	3.2±2.5	9.9±9.1
Cats 1–8	1 SD	1.9±2.2	3.0±1.4	1.2±1.0	6.1±4.2

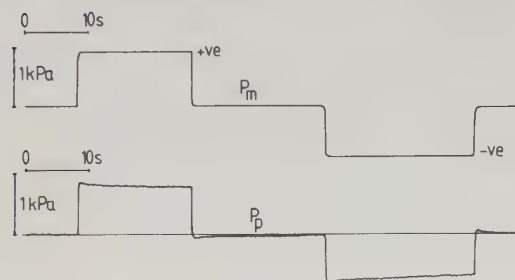


Fig. 5. Typical perilymphatic pressure response (P_p) to positive and negative pressure inputs (P_m) with a blocked cochlear aqueduct.

the perilymphatic pressure following the initial perilymphatic response. The area of the initial perilymphatic response peak then became significantly larger than that of the rebound response peak, and the ratio of these areas was significantly increased. The ratio of the areas was found to be directly proportional to the input pressure level and the duration of the stimulus.

DISCUSSION

The results of this investigation are in agreement with the results obtained regarding the initial perilymphatic response following the application of square waves by Densert et al. (17). In the previous investigation on inner ear pressure regulation, it was demonstrated that the perilymphatic pressure levels were more easily affected by middle ear stimulation than by stimulation via the ear canal. It was also shown in that study that stimulation of the ossicular chain led to poor pressure transmission to the inner ear fluids. In the present work, a transmyringal tube was used to transmit the pressure changes into the middle ear instead of drilling a hole in the bulla as was done previously (17). As the lumina of the Teflon tube and the hole drilled in the bulla were similar comparable pressure transmitting properties were obtained in both experiments. The Teflon tube was used in the present experiment in order to investigate methods of pressure transmission that could be applied to humans.

In the search for ways to influence the inner ear pressure levels by outside pressure changes, interest is focused in this work on the effects of middle ear pressure changes on the perilymphatic pressure. The method of calculation of the time constants used in the present study is, however, more accurate than the method previously used. An analysis of the second (rebound) phase of the perilymphatic pressure response has not been undertaken.

Table II. Ratio of the area of the initial pressure response to the rebound pressure response, a_1/a_2

Input pressures applied to the middle ear. Values given are mean for each cat ± 1 SD

Cat	a_1/a_2 input <3s	a_1/a_2 input ≈ 10 s
1	1.2 $\pm$ 0.2	1.3 $\pm$ 0.5
2	1.2 $\pm$ 0.2	1.2 $\pm$ 0.1
3	1.2 $\pm$ 0.2	1.3 $\pm$ 0.2
4	0.9 $\pm$ 0.2	0.9 $\pm$ 0.1
5	1.2 $\pm$ 0.1	1.3 $\pm$ 0.2
6	0.9 $\pm$ 0.1	1.1 $\pm$ 0.1
7	1.0 $\pm$ 0.2	1.2 $\pm$ 0.2
8	1.0 $\pm$ 0.1	0.8 $\pm$ 0.2

en before. The importance of the rebound phase is now more fully understood since it has been demonstrated that each perilymphatic pressure response contains almost equal amounts of positive and negative components when the cochlear aqueduct (CA) is patent. The perilymphatic fluid pressure response is quite different when the CA is blocked. Here the rebound component is greatly reduced. The stabilization rate of the perilymphatic pressure after blockage of the CA is very slow, giving an almost infinitely long time constant. The pattern of pressure stabilization shown by cats 9 and 10 is similar to that shown by cats where the CA was surgically blocked. It may be assumed that cats 9 and 10 had CAs with poor intrinsic patency. This implies that the CA plays a vital role in regulating the pressure in the inner ear hydrodynamic system.

The possibility of inducing a positive pressure change in the perilymphatic fluid seems then to be dependent on the pattern of the inner ear pressure stabilization, which, in turn, is mainly dependent on the patency of the CA, but other inner ear pressure release points may also be involved in the process of pressure stabilization.

The very long time constants observed after the blockage of the CA indicate that the pressure-regulating capacity of the endolymphatic system, perineural and perivascular spaces together, is far less than that of the CA alone. Nevertheless, the regulation of the physiological variations of the inner ear pressures appears to be well balanced even in individuals with poor patency of the CA, probably due to the close hydrodynamic relation between the endolymphatic and the cerebrospinal fluid systems (19).

According to investigations carried out by Tonndorf (14) on cochlear models, an increase in the volume of or pressure in the scala media greatly changes the hydrodynamic properties of the cochlear partition. It seems likely that a change in mass and elasticity of the cochlear partition in patients with Meniere's disease might also influence the function of other pressure release points, such as the endolymphatic duct and sac, particularly when there is a pressure gradient across the inner ear membranes. Since there is no technique available to separately evaluate the capacity of other inner ear pressure release points, their role in the regulation of inner ear pressure changes may only be speculated upon. Their importance should, however, be considered when external pressure changes are used in an attempt to influence the inner ear fluid balance in cases of endolymphatic hydrops.

It is generally accepted that the CA is patent in lower mammals (20, 21). The patency of the cochlear aqueduct in humans may differ from person to person (22, 23, 24), but we believe that with due caution it is possible to use the results of the experiments on cats as an aid to predicting the behaviour of a human ear to the same stimuli. Using a pressure chamber, we (11) demonstrated that the cochlear function of patients with Meniere's disease could be improved or made worse depending on whether the patient was exposed to an underpressure or an overpressure. The pathodynamics of these observations were not fully understood. It seems likely, however, that the induction of a positive pressure in the perilymph might influence the endolymphatic-perilymphatic fluid balance by a reduction in the volume of the endolymphatic fluid. On the other hand, the induction of a negative pressure change might well allow an increase in the volume of the endolymphatic fluid, thus aggravating the symptoms.

The results of the present study indicate, therefore, that the presence of a patent CA in humans could lead to methodological problems when trying to influence inner ear fluid balance in patients with Meniere's disease by means of square-wave pressure changes.

ACKNOWLEDGEMENT

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Transmission of Complex Pressure Waves through the Perilymphatic Fluid in Cats

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The response of the perilymphatic fluid to complex pressure waves, composed of low-frequency sine waves superimposed on square-wave pressure pulses of varying amplitude was studied. In cats with a patent cochlear aqueduct a pronounced positive pressure change could be induced in the perilymphatic fluid when complex pressure waves were used. The time constants associated with the stabilization of the perilymphatic pressure after the application of pressure complexes were longer than those associated with square-wave pulses alone. The results indicate that the functional patency of the cochlear aqueduct could be influenced by the transmission of complex pressure waves. The results also indicate that when trying to influence the inner ear hydrodynamic balance in patients with Meniere's disease, the effect of complex pressure waves is far superior to the effect of square-wave pressure pulses in patients with an open cochlear aqueduct. *Key words: Meniere, inner ear hydrodynamics, complex pressure waves*

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The normal functioning of the inner ear and its hydrodynamic system depends, to a great extent, on a well balanced ratio between the pressure in the perilymphatic and the endolymphatic fluid volumes, thus ensuring equal pressure on both sides of the membranous labyrinth and the basilar membrane. Disturbances in the inner ear fluid pressure have been regarded by numerous authors as an underlying cause of inner ear disorders (1, 2, 3). Rapid changes in ambient pressure and the application of high-level infrasound are known to produce different forms of inner ear dysfunction, probably by inducing a change in the inner ear hydrodynamics.

In order to gain a better understanding of the hydrodynamic processes in the inner ear, a method for direct measurement of the inner ear pressure transmission in cats was developed by Carlborg et al. (4). Further developments of the method allow study of the inner ear pressure regulating mechanisms, and also give information on the transmission of low-frequency pressure waves through the perilymphatic fluid (5). The results of these experiments made it possible to introduce a new way of influencing the inner ear symptoms in patients with Meniere's disease by means of locally applied pressure changes (6). The method was based on the hypothesis that a positive pressure change in the inner ear fluids, induced via the middle ear, would result in a compression of both the perilymphatic and the endolymphatic compartments. During a subsequent process of pressure stabilization, different inner ear pressure release routes might be activated, and excess endolymphatic fluid be extruded from the membranous labyrinth into adjacent fluid compartments. The induction of a negative pressure change in the inner ear might be expected to have the opposite effect on the inner ear fluid balance. In patients suffering from Meniere's disease exposed to relative underpressure in the middle ear, by using a pressure chamber, the symptoms (7) became exacerbated.

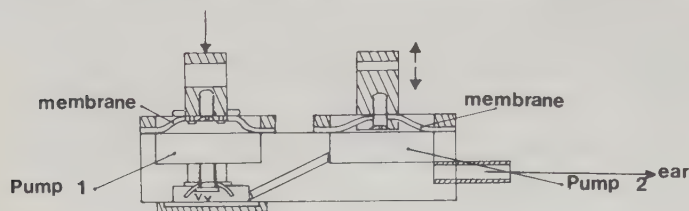


Fig. 1. Schematic illustration of the pressure generator. Pump 1 produces the square-wave pressure component and pump 2 the sine pressure waves. V_v is an adjustable valve for the release of pressure.

A recent investigation of the perilymphatic pressure response pattern to square-wave pressure pulses in the cat has shown that when the cochlear aqueduct is patent, each positive pressure change in the inner ear is followed by an almost equivalent negative pressure change (8). However, when the cochlear aqueduct is blocked, the negative response disappears almost completely. The possibility of influencing the inner ear fluid balance by means of overpressure seems then to be mainly dependent on the patency of the cochlear aqueduct. Poor patency of the cochlear aqueduct in humans has been demonstrated by Rask-Andersen (9). Other investigations indicate the possibility of an open communication channel between the perilymphatic compartment and the cerebrospinal fluid (10).

The purpose of this study was to investigate the response of the inner ear hydrodynamic system to the application of different types of complex pressure waves, i.e. low-frequency sine pressure waves superimposed on square-wave pulses. To study the effects of the transmission of different forms of pressure changes on the inner ear fluids, the experiments were performed on cats.

SUBJECTS AND METHODS

Fifteen healthy cats weighing between 2.3 and 3.5 kg were used in this investigation. The experiments were completed in 10 cats. They were anaesthetized with pentobarbital intravenously and tracheotomized. A purpose-built pressure generator was used for the induction of different forms of pressure waves. Fig. 1 is a diagram of the pressure wave generator. It contains two separate pumps, 1 and 2, which were used to generate square waves and low-frequency sine waves respectively. The design of the pressure generator was based on the requirement that the parameters of the pressure wave could be easily varied, and that a specific complex wave form could be accurately reproduced. The frequency of the sine pressure waves could be set within the range 5 to 15 Hz, and the amplitude could be varied from 0.5 to 3 kPa. The amplitude of the square-wave pulses could be varied from 0 to 5 kPa. When pressures exceeding 3 kPa were used, the Eustachian tube was blocked with epoxy resin. Pressures greater than 4.5 kPa were not used as these could cause damage to the middle and inner ear structures. The generator was equipped with an adjustable valve for the release of pressure. The duration of application of the pressure complexes could be varied from 0.5 s up to ≈ 15 s. Only positive pressure complexes were applied. Single square-wave pressure pulses were applied using a source of variable air pressure.

Pressure changes were applied and measured in the ear canal via polyethylene tubes fitted into the ear canal in a rubber stopper. The pressure changes were transmitted to the middle ear via a Teflon tube inserted into the tympanic membrane, thus bypassing the ossicular chain.

During the second stage of the experiment the cochlear aqueduct was blocked and the same series of pressure changes was applied to the middle ear in 4 cats.

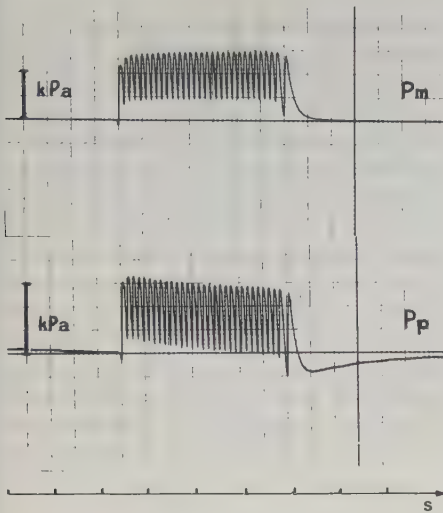


Fig. 2. An example of a recording from the transmission of a complex pressure wave through the perilymphatic fluid. A pronounced positive perilymphatic pressure is observed. P_m , middle ear pressure; P_p , perilymphatic pressure.

The perilymphatic pressure was monitored continuously throughout the experimental period via a small metallic cannula in the vestibulum which was connected to a pressure transducer and a specially designed low-noise amplifier. For details see Carlborg et al. (4) and Densert et al. (8).

After the experiments had been completed the tympanic cavity and the inner ear were dissected under an operating microscope and inspected for signs of haemorrhage or other damage.

The results were treated in the same way as in our earlier work (8). The time constants of the perilymphatic pressure response curves were calculated, and the areas below the initial and rebound perilymphatic pressure response curves were computed.

The value of the area below the initial perilymphatic pressure response curve represents the overall extent of positive pressure change. This area is referred to as the Integrated Positive Pressure Change (IPPC) and is defined as the area between the zero pressure line and half-way up the sine wave component, since the sine wave is symmetric about the square-wave maximum. The value of the area below zero pressure level represents the total extent of negative pressure change, and is referred to as the Integrated Negative Pressure Change (INPC). The ratio IPPC/INPC gives a measure of the positive pressure change transmitted to the inner ear in relation to the corresponding negative change for a given pressure application.

RESULTS

Low-frequency sine pressure waves, of frequencies 5, 10 and 15 Hz, superimposed on square waves of differing amplitudes were transmitted instantaneously to the perilymphatic fluid, as shown in Fig. 2. The time constants of the response of the perilymphatic fluid to these pressure complexes were calculated and compared with the time constants from the response to pressure steps of the same amplitudes. As can be seen in Table I, the time constants were, in general, increased by a factor 3 to 4 when pressure complexes instead of square-wave pulses were applied. In most cases, the amplitude of the 'rebound' perilymphatic pressure response was considerably smaller than the response to square waves. The use of different frequencies for the sine pressure waves did not seem to significantly influence the values of the time constants.

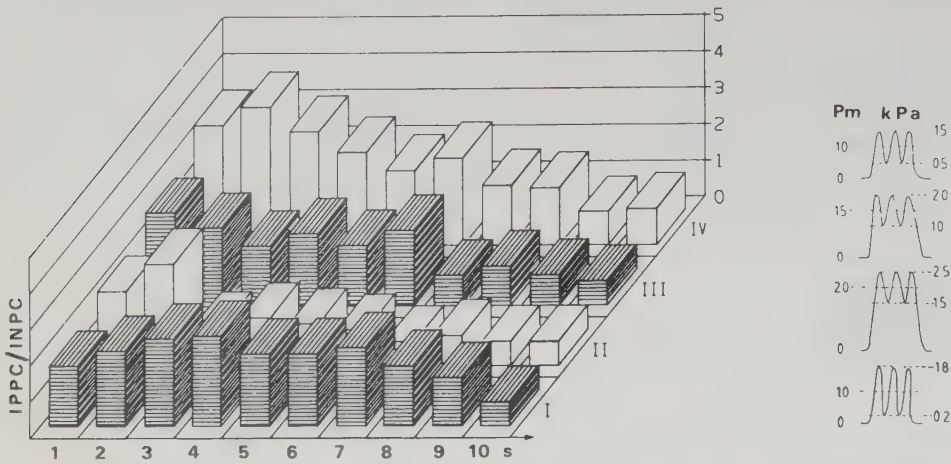


Fig. 3. The ratio IPPC/IPNC as a function of the duration of the input pulse for different pressure complexes. (The values shown are the mean values for 8 cats.) For details, see text.

In order to evaluate the relation between the pressure response in the perilymphatic fluid and the amplitude and duration of the input pulse, the ratio IPPC/IPNC was calculated. In Fig. 3 the ratio IPPC/IPNC is plotted as a function of duration of the input pulse for four different levels of sine pressure waves superimposed on square-wave pulses. The results are the mean values of 8 cats. It can be seen from the figure that the ratio falls between 2.0 and 3.5 when the amplitude of the pressure complexes was below 2 kPa and the square wave pressure was below 1 kPa. The highest value was obtained for combination IV: 0.5–1.5 kPa (peak to peak) sine waves and 1.0 kPa square-wave pressure. When the duration of the applied pressure change was less than 2 s the value of the ratio was almost independent of the duration. Increasing the pressure of the input caused a decrease

Table I. Comparison of the positive time constants (τ_1, τ_2) for the complex pressure inputs and the square-wave pressure inputs

The last two columns show the ratio of the time constants resulting from complex and square-wave pressure inputs. The mean values for each of 10 cats are given

Cat. no.	Input				Ratio Complex/Sq. wave	
	Complex		Square wave			
	$\tau_1^+(s)$	$\tau_2^+(s)$	$\tau_1^+(s)$	$\tau_2^+(s)$	τ_1^+	τ_2^+
1	6.2	—*	4.3	6.5	1.4	—*
2	22.6	—*	10.5	—*	2.2	—*
3	13.9	50.1	2.2	5.7	6.3	10.7
4	≈ 2	≈ 109	0.5	1.3	≈ 4	≈ 140
5	2.2	9.1	1.8	—*	1.2	—*
6	12.4	28.0	4.0	5.8	3.1	4.8
7	9.8	30.2	2.7	9.0	3.6	3.4
8	1.8	12.5	0.8	3.1	2.4	4.1
9	>100	—*	14.7	37.7	>10	—*
10	34.4	—*	29.2	28.8	1.2	—*

* No second time constant measurable.

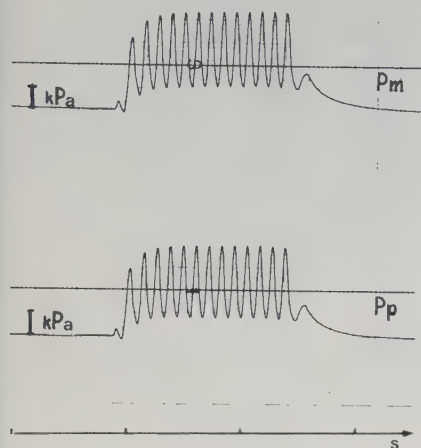


Fig. 4. An example of a recording of the transmission of a complex pressure wave through the perilymphatic fluid when the CA is blocked. P_m , middle ear pressure; P_p , perilymphatic pressure. Despite high pressure inputs (>4 kPa) a negative pressure response was not observed.

in the ratio. It can also be seen in the figure that the ratio dropped quickly for inputs of greater than 3–4 s duration. Input pressure changes of the order of 6 s and longer give rise to a ratio of ≈ 1 . Individual differences were seen, due to the different stabilization rates. In 2 cats, a slow stabilization was observed, which gave rise to much larger ratios, which increased with increasing input level and pulse duration. The effect was similar to that observed in cats with surgically blocked CAs.

In one of the cats the ratio IPPC/INPC was found to be between 0.5 and 1.0, and could not be increased with any combination of pressure parameters.

Varying the sine wave frequency did not seem to significantly influence the values of the ratios.

When the cochlear aqueduct was blocked, the rebound perilymphatic pressure response almost completely disappeared, causing the ratio IPPC/INPC to approach infinity. A typical response curve is shown in Fig. 4. The time constants became almost infinitely long and could not be measured.

DISCUSSION

In the search for ways to induce positive pressure changes in the inner ear fluids, various forms of pressure applications have been investigated. One earlier investigation showed that the inducement of a prevailing positive pressure response in the perilymphatic fluid was possible only when the cochlear aqueduct (CA) was blocked. It was therefore deemed necessary to investigate other ways of applying an overpressure which could give the required positive pressure effects in the inner ear fluids without surgically blocking the CA. Experiments on the transmission of low-frequency sine pressure waves demonstrated a positive pressure shift in cats showing a positive asymmetry of the initial perilymphatic response to positive and negative pressure changes (11). This pressure did not return to baseline but was maintained throughout the duration of the pressure application. This observation suggested that in individuals with an open CA, low-frequency sine waves superimposed on square waves (pressure complexes) could functionally influence the patency of the CA.

The specially designed pressure generator made it possible to test the effects of low-frequency sine pressure waves superimposed on square waves of different amplitudes

which were transmitted to the perilymphatic fluid. The rate of pressure stabilization after the application of complex pressure waves could be compared to that after the application of square waves with the help of time constants. In cats with a patent CA the time constants resulting from the application of pressure complexes are greater than the corresponding time constants resulting from the application of square waves (Table I). The results suggest that the inner ear hydrodynamic system behaves with an increased impedance when the pressure complexes are applied, compared with the application of pressure steps. In this hydrodynamic situation the functional patency of the CA is partially impaired. In order to estimate the extent of positive and negative pressure changes induced in the perilymphatic fluid, calculations of the areas above and below the zero pressure level were carried out. The rebound, negative pressure response was considered equivalent to the amount of fluid pressed out of the labyrinth.

Total amplitudes greater than 2.5 kPa gave a ratio of about 1 in most of the cats, which is similar to the results obtained in the transmission of square-wave pulses alone. Amplitudes exceeding 4.5 kPa were avoided, since intralabyrinthine bleeding and rupture of membranes had been observed at higher input levels (4). In one cat the ratio of IPPC/INPC could not be increased above 1 with any combination of pressure parameters. This indicates that the inducement of positive pressure changes may not be possible in some individuals because of their particular pattern of inner ear pressure stabilization. In 2 other cats, the ratios were substantially larger due to the poor intrinsic patency of the CA, suggesting that it may be possible to induce a prevailing positive pressure change in the inner ear fluids with a simple pressure step alone.

It may be concluded that in individuals with a patent CA the perilymphatic pressure ratio and the rate of pressure stabilization can be influenced by varying the parameters of the pressure complexes. In individuals with a reduced patency of the CA, high values of the ratio are recorded, irrespective of the pressure parameters. Further analysis of the effects of different pressure parameters on the perilymphatic pressure ratio may be possible if the problem is transformed into an electrical analogue.

The results of the present investigation did not demonstrate any significant differences in the perilymphatic response to varying sine wave frequencies. However, it may be assumed that the effect of sine pressure waves on the inner ear fluid balance is frequency dependent due to individual differences in the pressure-release capacity of the CA. The risk of damaging the inner ear structures is also likely to increase with increasing frequency.

The crucial point when trying to influence the inner ear pressure/volume relationship in Meniere's disease is to create a change in the levels of the inner ear fluid pressure which will cause a displacement of the endolymphatic fluid. Difficulties with this approach lie in the fact that, while the whole labyrinthine space is exposed to pressure changes, it is the volume of the endolymphatic fluid which is to be decreased.

On the basis of the current results it is assumed that an increase in the inner ear pressure may stimulate a flow of endolymph out of the membranous labyrinth. Several routes of transportation of the endolymphatic fluid may be involved. Besides the endolymphatic duct and sac, it has been reported by Duval et al. (12) that the vascular stria is important for the regulation of the endolymphatic volume. An increase in the passage of water molecules across the inner ear membranes, due to an increase in the hydrostatic pressure, has been considered as one possible mechanism influencing the endolymphatic fluid volume by outside pressure changes (13). According to Allen's calculations (13) a considerable amount of hydrostatic pressure would be needed to reduce the volume of the endolymphatic fluid.

The knowledge concerning the function of the patency of the CA in the transmission of

different forms of pressure gained in these experiments may be extrapolated to humans. The pattern of inner ear pressure stabilization in humans may, however, have other characteristics. The results of studies on the patency of the human CA differ widely. Some authors claim that the CA is not patent at all in adults, while others have found an open CA in the majority of human temporal bones (9, 14). In a pilot study on Meniere patients treated with overpressure it was found that the inner ear symptoms in some cases could be influenced by applying square wave pulses. The other patients required the application of pressure complexes in order to relieve the symptoms (6), which may be interpreted as evidence that the presence of an open CA is not unusual in adults.

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QUANTIFYING PSYCHOACOUSTIC TUNING CURVES FOR CLINICAL USE

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ABSTRACT

Quantifying psychoacoustic tuning curves for clinical use. Densert, B., Kinberger, B., Arlinger, S. and Densert, O. (Departments of Otolaryngology and Clinical Chemistry, Halmstad Hospital, Sweden and Audiology, University Hospital, Linköping, Sweden).

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Psychoacoustic tuning curves (PTCs) were obtained in a number of normal-hearing and hearing-impaired subjects using a simultaneous tone-on-tone masking technique. PTCs at three different centre frequencies (500, 1000 and 2000 Hz) were studied. In order to estimate the degree of frequency selectivity of the inner ear, an algorithm for quantification of PTCs was constructed. The method of linear regression was used to calculate the slopes of the linearized curves. Three different parameters of the curve, the low and high frequency slope and the height of the curve, were calculated using computer programs which allowed automatic evaluation of the data. The values of these parameters concerning normal and hearing-impaired subjects are presented in terms of scores and percentages of normal values. The algorithm for quantification of PTCs presented in this paper may in clinical work serve as a method of evaluating auditory frequency selectivity, particularly for very abnormal PTCs.

Key words: psychoacoustic tuning curves, frequency selectivity

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INTRODUCTION

It is generally assumed that the mechanical vibration of the basilar membrane provides the basic pattern for frequency analysis in the peripheral auditory system (Fletcher, 1940; von Békésy, 1960). However, studies on excitation patterns of the single auditory nerve fibres showed greater acuity of frequency analysis than could be accounted for by the frequency-resolving power of the basilar membrane alone (Møller, 1970; Zwislocki, 1974). Intracellular recordings from the organ of Corti showed that the same degree of spectral analysis, which had been found at the auditory nerve level, was already

present in the inner ear hair cells, indicating that other physiological mechanisms contributed to the frequency sharpening at the pre-neural level (Russek & Sellick, 1978).

Similarities in the shape of neural tuning curves and masked audiograms using pure-tone or narrow-band masking, indicated that psychoacoustic analogues of neurophysiological tuning curves might be obtained at the behavioural level in humans using simultaneous or forward masking techniques (Egan & Hake, 1950; Scharf, 1971). Such masking curves are called psychoacoustic tuning curves (PTC). Investigations of the inner ear function in hearing-impaired subjects have been conducted by several researchers, using PTCs. The general pattern of pathological PTCs has been established in different groups of patients with hearing loss (Leshowitz & Lindström, 1977; Zwicker & Schorn, 1978; Florentine et al., 1980). A qualitative correlation has been found between cochlear impairment and reduction of frequency selectivity. Broadening of the curve, reduction of the tip and elevation of the thresholds of the PTCs have been described. More exact methods of quantifying the PTCs are not available, however. Attempts have been made to describe the shape of the PTCs by the Q10 value (quality factor), which is defined as the centre frequency divided by the bandwidth, 10 dB above the test tone level. However, this method cannot be applied to many of the grossly abnormal PTCs seen in subjects with moderate or severe sensorineural hearing loss, e.g. in Meniere's disease.

Meniere's disease represents a specific inner ear disorder where fluctuations in hearing function may be directly related to a change in the endolymphatic fluid volume/pressure (Hallpike & Cairns, 1938; Tonndorf, 1967). The development of a method of influencing the inner ear function in Meniere's disease by means of overpressure (Densert & Densert, 1982) created a need for quantitative measurements of frequency selectivity.

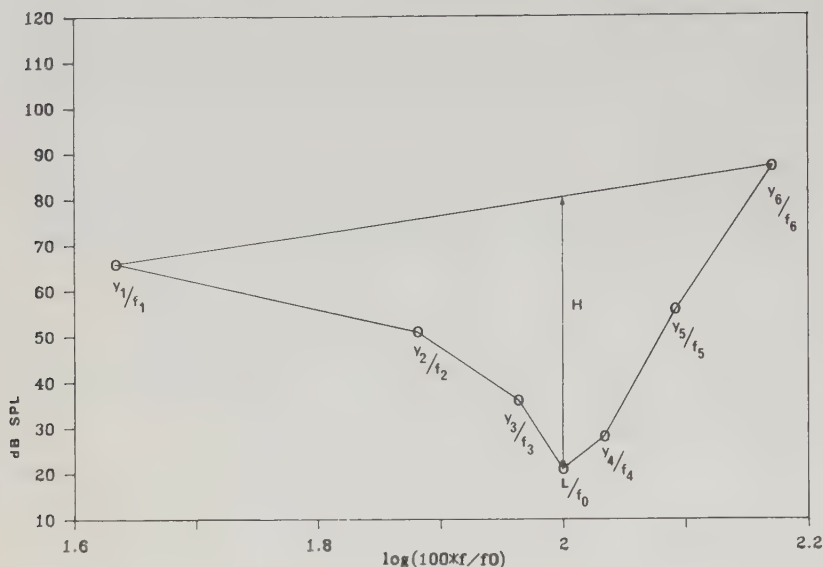


Fig. 1. PTC from a normal-hearing subject. The "tail" and the "steep" parts are indicated by y_1, y_2, y_3 and y_4, y_5, y_6 respectively. y_1 – y_6 are the masker levels at frequencies required to mask the test tone at frequency f_0 and level L . The parameter H is also shown.

Measurements of frequency selectivity by means of PTCs seemed to be one way of evaluating the degree of cochlear disorder caused by changes in the mechanical properties of the cochlear partition. The aim of the present study was to present a simple method of quantifying the PTCs for clinical use, which could be used also when the PTC deviates significantly from the normal shape. The method was to be applied on subjects with Meniere's disease during the exposure to pressure changes, and thus test-retest reliability was an important characteristic.

MATERIALS AND METHODS

Subjects

Ten normal-hearing subjects, aged 20–30, were tested. They showed normal hearing threshold levels within 10 dB (re. ISO 389, 1975) at all frequencies tested.

The PTCs were obtained at centre frequencies of 500, 1000 and 2000 Hz. Measurements of speech discrimination and the stapedius reflex threshold showed normal values.

Ten subjects with a hearing loss caused by Meniere's disease were also tested. PTCs were obtained at the same centre frequencies. The hearing loss in these subjects ranged from 50 to 70 dB PTA. The diagnosis of Meniere's disease was based on the history, a thorough medical examination, and audiometric findings. The subjects had not received any treatment for at least 3 months prior to the tests.

Technical equipment

A Madsen OB 70 audiometer was used to generate the intermittent test tone, which was presented with a rate of

2/sec and 50% duty cycle. Test tone frequencies used were 500, 1000 and 2000 Hz. A specially built pure-tone generator was used to produce the masker tones. The following masker frequencies were used. For the 500 Hz test tone: 215, 380, 460, 540, 615 and 740 Hz. For the 1000 Hz test tone: 430, 760, 920, 1080, 1230 and 1480 Hz. For the 2000 Hz test tone: 860, 1520, 1840, 2160, 2460 and 2960.

The test tone from channel 1 of the audiometer and the masker tone from the pure-tone generator were synthesized, amplified, attenuated and led monaurally to an earphone, Telephonics TDH-39 with MX-41/AR. A Danplex AS 72 audiometer providing a narrow-band masking noise was used when the difference in hearing threshold levels between the tested and non-tested ear required masking of the non-tested ear. The whole system was calibrated in accordance with re. ISO 389, 1975. Measurements were conducted in a sound-attenuated room. A microcomputer, IBM PC (IBM Corp., CA, USA), with 256 K memory and equipped with dual floppy disk drives, a graphic printer and an A3 plotter (Hitachi Corp., Japan) were used throughout the work. All calculations were performed with the microcomputer calculation program Lotus 1–2–3 (Lotus Corp., USA).

Psychoacoustic testing procedures

The measurements of the PTCs began by determining the hearing threshold for the test tone. The test tone was then increased by 10 dB and fixed in level. The continuous masker tone and the intermittent test tone were then presented simultaneously to the same ear. The level of the masker tone was determined, in 5-dB steps, by finding the level which just masked the test tone. The frequencies of the masker, three below and three above the test frequency, were presented to the subject in a random order. In this way in each testing procedure, one test tone level and

Table I. Frequency selectivity in normal-hearing subjects, average values and standard deviations (SD) for 10 subjects

Parameter f_0	500 Hz	1 000 Hz	2 000 Hz
	(1 SD)	(1 SD)	(1 SD)
Y1 dB SPL	64.5 (5.4)	65.5 (5.0)	65.0 (5.9)
Y2 dB SPL	52.5 (5.7)	52.3 (4.4)	54.3 (4.3)
Y3 dB SPL	39.8 (6.6)	39.5 (3.9)	41.3 (4.4)
Ref. tone dB SPL	27.5 (2.7)	25.0 (2.8)	26.0 (3.9)
Y4 dB SPL	32.8 (3.4)	29.8 (4.4)	32.9 (4.3)
Y5 dB SPL	49.5 (6.5)	48.9 (5.9)	54.8 (6.5)
Y6 dB SPL	77.3 (4.9)	82.5 (6.7)	83.0 (3.9)
Height =			
H dB SPL	45.7 (3.7)	52.2 (6.2)	51.0 (5.6)
Slope of tail k_t	28.9 (6.2)	30.7 (8.0)	27.8 (6.7)
Slope of steep k_s	55.7 (7.3)	65.9 (11.2)	62.8 (10.0)
Total score	100 (11.6)	100 (15.8)	100 (14.8)
Height score	20 (1.6)	20 (2.4)	20 (2.2)
Tail score	40 (8.6)	40 (10.4)	40 (9.6)
Steep score	40 (5.2)	40 (6.8)	40 (6.4)

six masker levels were obtained. The PTC tests were repeated in all subjects within 2–3 hours in order to provide data for the evaluation of test–retest reliability.

COMPUTATIONAL PROCEDURE AND RESULTS

Fig. 1 shows a plot of the PTC, as masker level in dB vs. $\log(100 \cdot (f/f_0))$, from a normal-hearing subject. The test tone frequency is f_0 and the six masker frequencies are denoted by $f=f_1, \dots, f_6$. The curve is asymmetrical and non-linear and experimental data are not easily fitted by a mathematical function.

In order to facilitate the mathematical evaluation, the curve was split up into two parts. The left part is referred to as “tail” and the right part as “steep”. The tail part corresponds to frequencies $f < f_0$ and the steep part to $f > f_0$.

The following transformation of the f/f_0 variable was performed:

$$(I) \quad x' = 100(1 - f/f_0) = \text{tail}$$

$$(II) \quad x' = 100(f/f_0 - 1) = \text{steep}$$

x' represents the relative distance in frequency between masker and test tones. This quantity is then plotted on a logarithmic scale:

$$(III) \quad x = \log x'$$

The tail and steep functions may both be written as:

$$(IV) \quad y = kx + l \quad k = \text{slope, } l = \text{intercept on the } y\text{-axis,}$$

y = masker level in dB SPL.

Three data points from the tail (y_1, y_2 & y_3) and steep (y_4, y_5 & y_6) parts of the PTC were fitted. The best-fitting straight lines, as described by the equation (IV) through the data points were calculated using linear regression analysis. Curves were derived from normal-hearing subjects.

The linearity was checked for both tail and steep functions. The correlation coefficients (r) were as follows:

$$r(\text{tail}) = 0.98 \pm 0.06 \text{ (95 \% confidence limits)}$$

$$r(\text{steep}) = 0.98 \pm 0.04 \text{ (95 \% confidence limits)}$$

indicating that the experimental data are well fitted by straight lines. However, the regression lines for the masker data points will not fit the data point of the test tone. In order to describe the position of the data point of the test tone, a third parameter, H , is introduced. H is defined as the vertical difference between the test tone data point (L) and a line joining the extreme points (y_1/f_1 and y_6/f_6) of the PTC, as shown in Fig. 1. By means of simple geometric calculations, it can be shown that H can be determined by the following equation:

$$(V) \quad H = y_1 + (y_6 - y_1) \frac{\log f_0 - \log f_1}{\log f_6 - \log f_1} - L$$

The characteristic properties of the PTC function may thus be expressed by three parameters:

k_t (the slope of the line fitting the tail part of the PTC)

k_s (the slope of the line fitting the steep part of the PTC), and H . Fig. 2, A and B show the PTCs from one normal-hearing and one hearing-impaired subject, respectively. Fig. 2, C and D show the corresponding results after the transformation of the fre-

Table II. Differences in scores obtained at test–retests in 10 normal-hearing and 10 hearing-impaired subjects; results analysed by means of t -test

Subjects	f_0 (Hz)	Mean	SD	95 % Confid. interval
Normal-hearing ($n=10$)	500	−0.6	9.4	−0.6 ± 6.7
	1 000	−3.4	7.6	−3.4 ± 5.4
	2 000	4.6	7.4	4.6 ± 5.3
Hearing-impaired ($n=10$)	500	0.4	4.1	0.4 ± 2.9
	1 000	1.0	1.9	0.8 ± 1.4
	2 000	−2.2	3.7	−2.2 ± 2.6

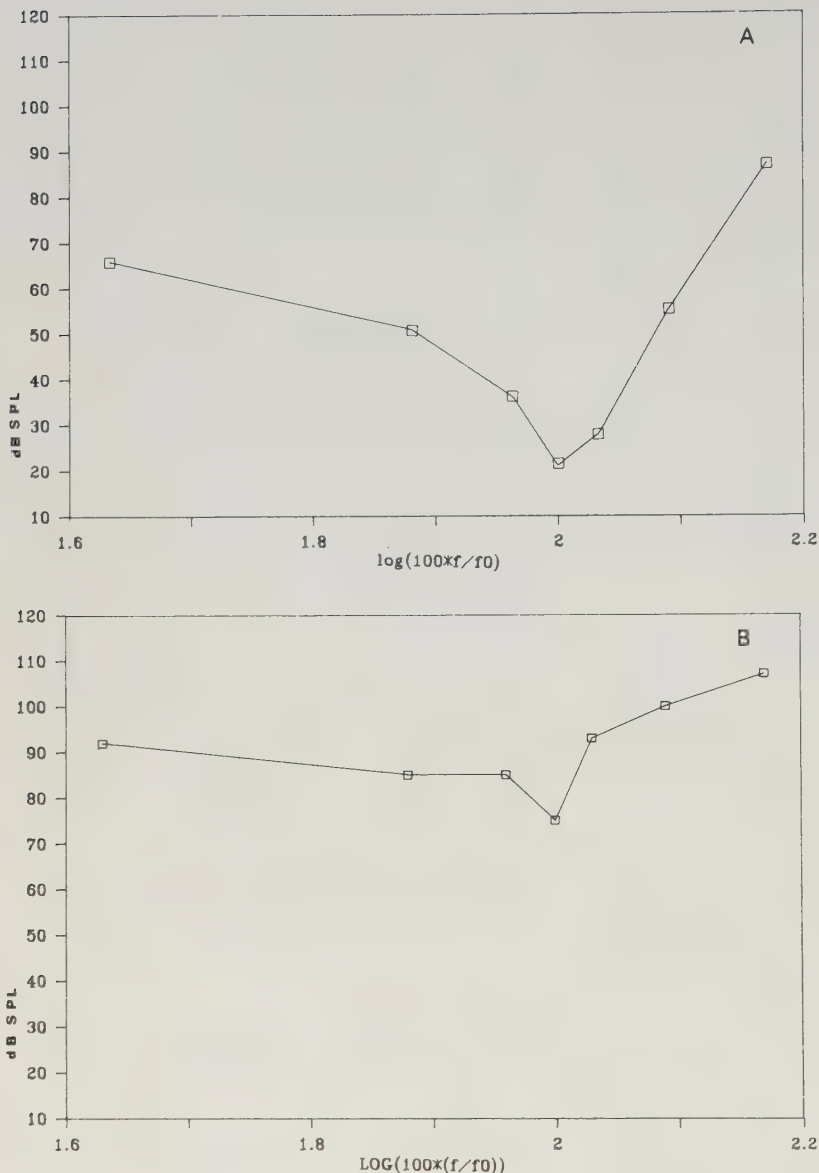


Fig. 2. PTCs from a normal-hearing (A) and a hearing-impaired (B) subject are shown. In C and D, the fits to the data points for the tail ($\square$) and steep ($+$) parts of the PTC are shown for normal-hearing and hearing-impaired subjects, respectively.

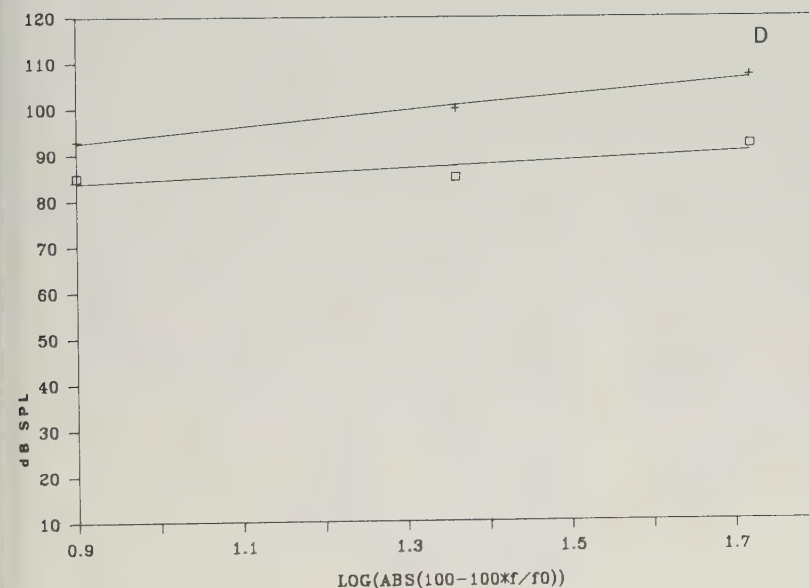
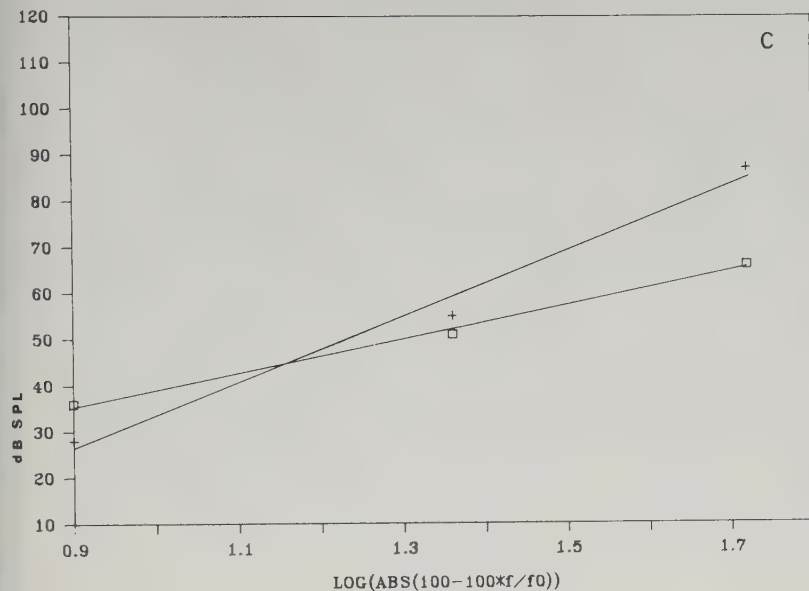
quency axis as defined by eq. (I), (II) and (III), and the calculated regression lines.

A score system was devised, based on mean values of these parameters from normal-hearing subjects. This system allows a simple quantitative evaluation of PTCs obtained in individual patients in relation to normal-hearing subjects.

The frequency resolution is primarily represented by the slopes of the PTCs. We assume the tail and the steep slopes to be equally important. The k_t and k_s -values were therefore both transformed into scores between 0 and 40.

The parameter H is closely related to k_t and k_s when their values clearly exceed zero. When the values of k_t or k_s approach zero as in cases of very poor frequency selectivity, H may vary independently of the slopes. Thus, it was considered reasonable to reduce the influence of the H parameter on the total score, and the range 0–20 was therefore chosen. The total score is determined from the formula:

$$(VI) \text{ Total score} = 40 (k_t/k_{tn}) + 40 (k_s/k_{sn}) + 20 (H/H_n)$$



(Total score=Tail score+Steep score
+Height score)

The index n indicates the mean normal value.

The total score in an average normal-hearing subject will thus be 100. In Table I the results obtained on the normal-hearing subjects at the test frequencies 500, 1000 and 2000 Hz are presented in terms of the mean values of the masker levels with 1 SD. The values of the three parameters H , k_t and k_s (1 SD) are also given. Finally, the corresponding partial and total scores are shown.

The data from the hearing-impaired subjects were analysed in the same manner. The frequency resolution was considerably poorer in all patients belonging to this group at all frequencies tested. There was also a considerable variation in individual scores. Fig. 3 shows how the score system reflects a decrease in frequency selectivity in subjects with advanced hearing losses due to Meniere's disease.

The results from the test-retest procedures were analysed in terms of scores. Calculations of differ-

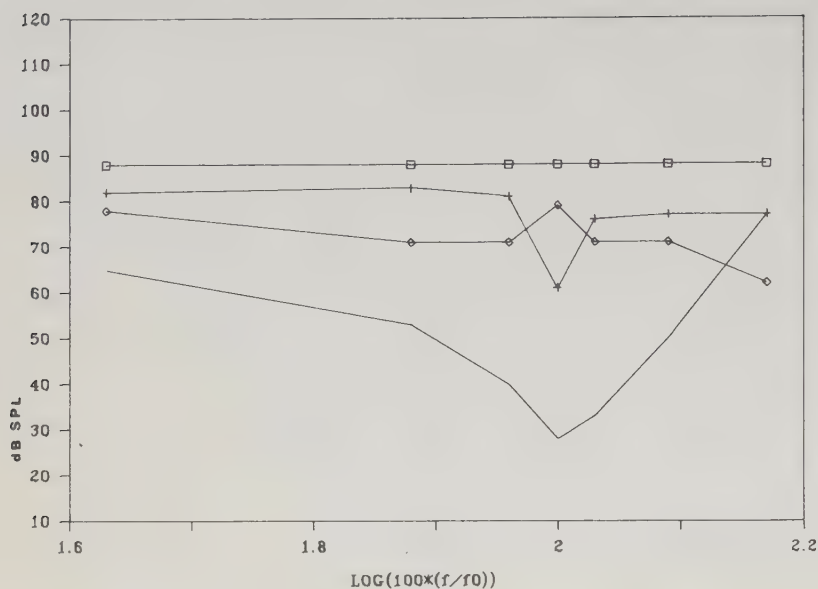


Fig. 3. PTCs obtained from 3 subjects with sensorineural hearing loss due to Meniere's disease. $\square$, A PTC with a total score of 0; +, a PTC for which the score was calculated to 10; $\diamond$, a PTC with -3 in scores, owing to the inverted peak and descending shape of the steep part. The average PTC derived from the normal subjects is also shown. Test tone frequency is 500 Hz.

ences in scores from the tests and retests were performed. The results are shown in Table II. The differences between the scores were tested by means of the null hypothesis, $H(0)$: the average difference in scores is not different from zero. The results showed that the null hypothesis $H(0)$ could not be rejected at the 95% confidence level. This was true for both the normal-hearing and hearing-impaired subjects.

Table II also shows that the standard deviations for test-retest differences obtained in the hearing-impaired group were smaller than those of the normal-hearing group. The standard deviations of 2-4 dB obtained in the impaired group are about half the magnitude of those found in the normal group.

DISCUSSION

In the present study, a simultaneous masking technique as that described by Zwicker & Schorn (1978), was used. This testing procedure proved easy to perform in daily clinical work. The curves obtained from normal-hearing subjects showed good frequency selectivity, which increased with increasing frequency of the test tone. A difference between the shape of the tail and steep parts of the PTC was clearly shown.

The shapes of the curves from subjects with a severe sensorineural hearing loss showed an almost

complete loss of the normal pattern of frequency selectivity. These results agree closely with those obtained by other investigators (Leshowitz & Lindström, 1977; Zwicker & Schorn, 1978; Florentine et al., 1980).

While a qualitative evaluation of the general shape of the PTCs may be easily made, the quantitative comparison between results concerning frequency selectivity is a complex matter. Describing the PTCs in terms of Q 10 has been a useful method of measuring frequency selectivity in normal-hearing subjects. In subjects with advanced cochlear pathology, the shape of the PTC may be very distorted and Q 10 may then have a limited value. The method described by Patterson (1976) of estimating the auditory filter in terms of the 3-dB bandwidth is equally limited on many pathological PTCs.

In order to describe more fully the shape of the PTC, the low- and the high-frequency slopes of the curve were analysed separately in this work.

The method of linear regression with a logarithmic frequency scale has been used to quantitatively determine the slopes of the two parts of the tuning curve. The height of the curve at the test frequency describes the range of sensitivity of the inner ear in response to the masked and unmasked listening situation. These three parameters are considered to be representative of the inner ear frequency selectivity, although the influence of the height was reduced in the scoring system. The height parameter

may be closely related to the slopes of the tuning curve in normal-hearing subjects. In hearing-impaired subjects, it may vary independently of the values of the slopes and is therefore assumed to be a less significant characteristic of the PTC.

The system of scoring built on these assumptions is expected to reflect the degree of frequency selectivity in both normal-hearing and in particular hearing-impaired subjects and may be useful in making comparative estimations of frequency selectivity function. In order to estimate quantitatively the frequency selectivity in hearing-impaired subjects, the values obtained from each subject are related to the average normal frequency selectivity, i.e. derived from the values of normal-hearing subjects.

The individual scores approach zero when the frequency resolution is completely dissolved. In patients with an advanced hearing impairment, values of the parameters may even become negative, due to distorted, reversed direction of the slopes of the curves.

Investigations on inner ear frequency selectivity in subjects with advanced hearing losses, >60 dB PTA, indicate that the shapes of the PTCs may be greatly influenced by increased non-linearity of the inner ear response (Zwicker & Schorn, 1978). It is therefore considered that PTCs obtained in these cases should be interpreted with caution.

Estimation of the error involved in the process of psychoacoustic testing procedures is thus of the utmost importance when conclusions are drawn concerning the inner ear frequency selectivity on the basis of PTC measurements. The results from the test-retest procedures were analysed in order to estimate the reproducibility of the PTCs. Subjects with a sensorineural hearing loss, of <70 dB PTA, showed a good ability to reproduce the result. In our experience, subjects with a hearing loss of >70 dB PTA had difficulties in reproducing the PTCs because of the masking levels approaching uncomfortable levels, and because of the appearance of interference tones.

Analysis of differences in scores from the test-retests indicated that a variation in scores within 8–10 units might be attributed to the method of measurement. Larger variations may be due to factors other than the test technique itself, e.g. spontaneous or induced changes in auditory function. However, the data reported here were obtained on rather small groups and more experience is certainly desirable.

The computer technique, presented in this paper, allows storing and processing of large amounts of data and may provide a feasible clinical method of quantification of frequency selectivity in different inner ear disorders.

Quantifying the PTCs may provide a model for studying the dynamics of the cochlear pathology in sensorineural hearing loss with spontaneous or induced changes.

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Effects of Overpressure on Hearing Function in Meniere's Disease

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Densert B. Effects of overpressure on hearing function in Meniere's disease. Acta Otolaryngol (Stockh) 1986.

The relationship between ambient pressure changes and hearing function was investigated in 14 patients with well-defined sensorineural hearing losses caused by Meniere's disease. The period of exposure to pressure changes varied individually between one and 4 months. The evaluation of hearing function was made by means of pure-tone audiometry, speech discrimination tests and psychoacoustic measurements of the inner ear frequency selectivity. Significant changes were found in the hearing parameters in relation to the period of pressure application. The use of psychoacoustic tuning curves allowed spatial observations on changes in the frequency selectivity. This method proved to be of particular value in the assessment of the inner ear function in Meniere's disease. The results support the hypothesis that the use of overpressure creates a change in the hydrodynamic properties of the cochlea, reflected in an improvement of the inner ear frequency analysis. *Key words: Meniere's disease, hearing function.*

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Evaluation of the results of treatment in Meniere's disease poses considerable difficulties because of the natural course of the disease which is characterized by spontaneous remissions and exacerbations of symptoms. Vertigo seems particularly difficult to evaluate objectively in relation to treatment. In most patients, vertigo becomes less disturbing as the disease progresses (1), whereas a hearing impairment becomes a lasting handicap in most cases. A long-term study on a large number of patients, conducted by Stahle (2), showed that hearing in the average patient deteriorated early after the onset of the first symptoms. It has been assumed that the hearing loss consists of an irreversible component, which after each period of exacerbation progresses as the result of an increasing permanent distension of the inner ear membranes (3, 4).

Advances in inner ear surgery in recent years have provided a variety of ways to shunt the inner ear fluids (5, 6). There is, however, still no evidence that the hearing function may be significantly improved by any of these methods, and it has been questioned whether the inner ear hydrodynamic balance in Meniere's disease is influenced by sac surgery (7, 8). Restoration of hearing in Meniere's disease by means of ambient pressure changes was first attempted in a pressure chamber on patients with acute symptoms (9).

Increased knowledge of the transmission of pressure changes through the inner ear fluids was needed in order to pursue a hypothesis that the inner ear hydrodynamics could be influenced by external pressure changes. Experimental investigations on the inner ear pressure regulating mechanisms indicated ways of influencing the inner ear fluid pressure relations by exposure to pressure changes (10, 11). Recent studies on the transmission of square wave pressure pulses and complex pressure changes have been carried out to investigate ways of inducing a positive pressure change in the inner ear fluids (12).

In a group of patients with long-standing hearing losses caused by Meniere's disease, different forms of overpressure were tried. The results from this study indicated that such pres-

sure applications could provide a new way of improving the hearing function in patients suffering from Meniere's disease (13).

Theories on the origin of the hearing loss in Meniere's disease have indicated that the endolymphatic hydrops causes a mechanical impairment of the basilar membrane, affecting its frequency-filtering function (4, 14). Psychoacoustic tuning curves (PTCs) reflect the mechanical frequency-resolving power of the basilar membrane and may serve as a measure of functional change in the inner ear (15). Compared with measurements of pure-tone audiometry which reflect detection sensitivity, measurement of PTCs, reflecting frequency resolution, thus seems to be an adequate tool for spatial studies on the function of the cochlear partition.

A computer model based on frequency selectivity data from normal-hearing subjects was developed to study hearing function in various inner ear disorders (16). The model allows quantitative evaluations of the changes in hearing function in patients with Meniere's disease to be made in relation to pressure changes. The aim of this study was to investigate the relationship between changes in hearing function in patients suffering from Meniere's disease, and exposure to overpressure.

SUBJECTS

The study comprised 14 patients with an average age of 50 years (16–67). Recurrent vertigo, fluctuating hearing loss and a feeling of aural pressure were the main criteria for the diagnosis of Meniere's disease (17, 18). The diagnosis was established on the basis of a history of symptoms, medical examination, and audiometric tests which included pure-tone audiometry, speech discrimination scores, psychoacoustic tuning curves, tympanometry, and the measurements of stapedius reflex thresholds. The caloric test was carried out. Allergic and metabolic disorders were excluded by means of appropriate tests.

X-ray studies on the temporal bone were made. The possibility of an acoustic neuroma, as well as malformations within the os petrosum were ruled out. The glycerol test was found to be positive in 3 patients, while the remaining 11 patients did not respond to the glycerol intake. The average duration of the symptoms was 8 years. The longest duration of the disease was 15 years (3 patients), and the shortest 1 year (1 patient). The hearing loss of the patients included in the study did not exceed 65 dB PTA (average of 500, 1 000 and 2 000 Hz), and was not less than 45 dB PTA.

Two of the patients showed the ascending type of hearing loss. One of these patients experienced a fluctuation in hearing only 5 weeks before the induction of pressure changes and also showed the shortest duration of symptoms (1 year). In the other patient, hearing threshold levels remained stable for 6 months before exposure to pressure changes.

Two patients had an ascending–descending type of hearing loss. Hearing threshold levels remained essentially unchanged in these 2 patients for 5 and 8 months, respectively, before the start of pressure applications.

Ten patients showed a sensorineural hearing loss of flat or flat–descending type. No signs of positive fluctuations in hearing threshold levels >10 dB PTA were noted in these patients for 8–12 months before exposure to pressure changes.

The disease was bilateral in 3 patients. Only one ear was reported from each patient. In 2 of the patients, the hearing loss in the contralateral ear was >65 dB PTA. In the third patient, the other ear had been destroyed earlier because of a disabling vertigo. In 7 patients, vertigo interfered with daily activities at the time of admission to the clinic. In 2 patients, vertigo was only occasionally observed, and in 4 patients there was no vertigo for at least 6 months before admission. One patient had only cochlear symptoms and no vertigo at all. The symptom of fullness was reported by 11 patients.

METHODS

Technical equipment

For the PTC tests, a Madsen OB 70 audiometer was used to generate the intermittent test tone. Test-tone frequencies used were 500 and 2000 Hz. A purpose-built pure-tone generator was used to produce the masker tones. Six different masker frequencies, close to the test frequency, were used. A Danplex AS 72 audiometer providing a narrow-band noise was used for masking the contralateral ear. The system was calibrated in accordance with ISO 389 1975.

A specially constructed pressure generator was used for the induction of pressure changes. The generator contained two separate pumps which produced static pressure and sine pressure waves. The static pressure levels and the amplitude of the sine pressure waves could be adjusted separately. The duration of the pulse and the pause between the pulses could be adjusted (12).

Audiological tests

The patients were followed by repeated measurements of pure-tone and speech audiometry for 8 to 12 months before the start of pressure application and during the period of exposure to pressure changes which varied between 2 and 4 months.

The PTCs were obtained by means of a simultaneous masking technique. The test frequencies were 500 and 2000 Hz. The patients were trained in the technique of PTC testing before data collecting was started. The test tone was presented at a sensation level of 10 dB. The masker tone was presented to the same ear, simultaneously with the pulsed test tone, and the highest masker level just permitting the test tone to remain audible was determined for the six masker frequencies (19). The healthy ear was masked by a narrow-band noise when the difference between the bone conduction thresholds of the tested vs. the contralateral ear so required.

The PTCs were evaluated by calculating an index, where 100 corresponded to the average results of normal ears and 0 was obtained for a completely flat PTC (16).

Pressure application procedure

Pressure applications were administered in the ear canal and transmitted to the middle ear via a transmyringal Teflon tube inserted in the tympanic membrane. The applied pressure changes contained sine waves of about 9 Hz, superimposed on a static pressure. The total amplitude did not exceed 2 kPa. The ratio of the sine wave and static pressure components was kept at about 2:1 and the length of the pulse was <2 s. About 10 stimuli/min were presented for several minutes, and the exposure was repeated several times a day. The number of exposures was adjusted individually.

A feeling of fullness, tinnitus and daily evaluations of hearing function were guidelines for the adjustment of pressure parameters during the initial period, which varied from one week to 10 days. The total period of treatment extended from one to 4 months, during which frequent measurements of pure-tone thresholds, speech discrimination and PTCs were made.

The exposure was terminated when the improvement could be considered satisfactory. The period of exposure after which evaluation of hearing function was to be performed, was extended to 4 months.

RESULTS

Relief of the sensation of fullness and pressure in the ear was commonly observed as a first sign of improvement. This effect was obtained in patients within a few days after the start

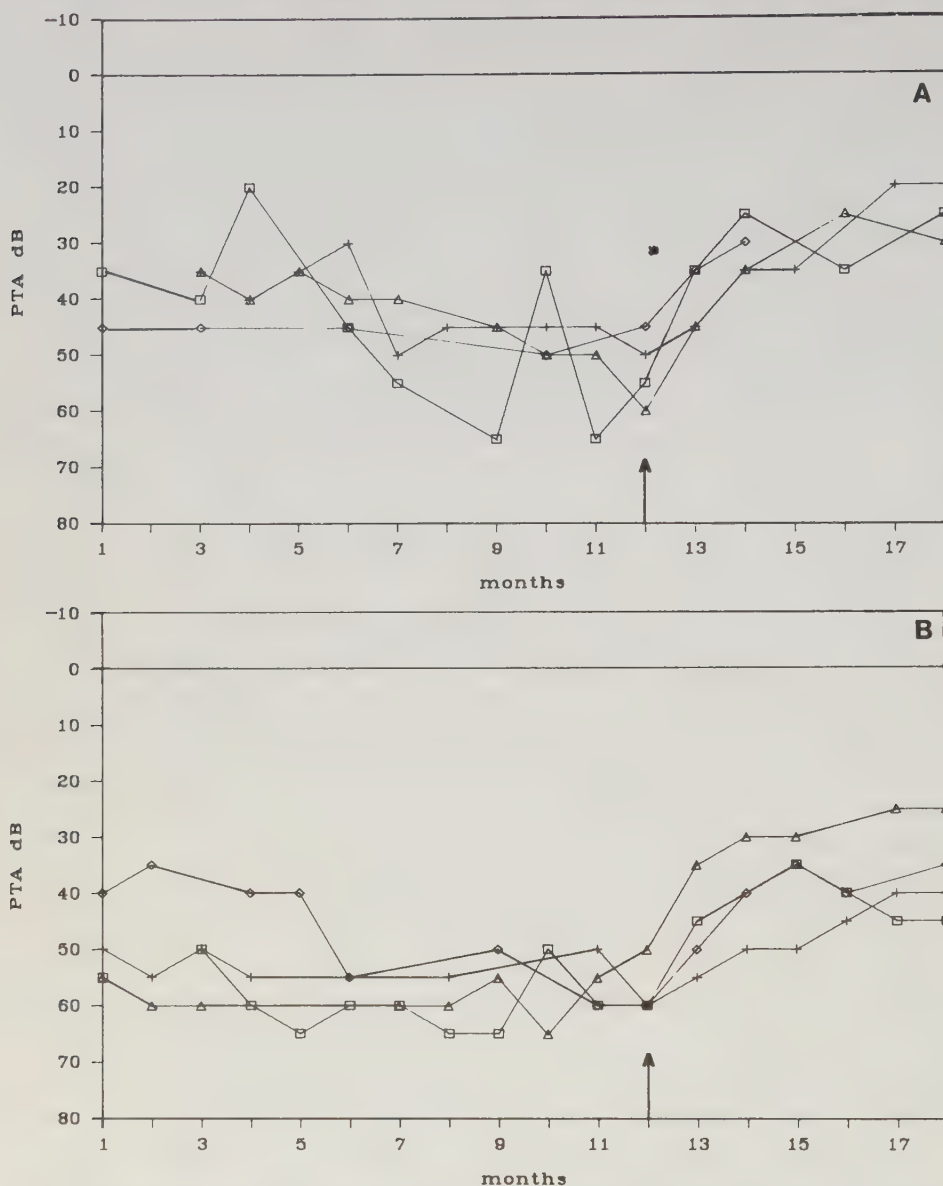


Fig. 1. The results of repeated measurements of pure-tone audiometry (PTA of 500, 1000 and 2000 Hz) are shown as a function of time in patients 1, 2, 3 and 4 (A), and in patients 9, 10, 11 and 12 (B). The arrow indicates the start of pressure application.

of the pressure application. In the patients suffering from vertigo, relief from this symptom was seen within a few days up to 2 weeks.

Improvement in hearing was recorded in 12 out of 14 patients. Two of the patients showed no significant change in any of the hearing parameters. None of the patients became worse during the period of pressure application. The improvement in hearing took place gradually within a period of a few days up to 2 weeks after the start of pressure application. Changes in the hearing parameters continued, and in the majority of patients an optimal effect on

Table I. Data describing the symptomatology and results concerning the hearing parameters

Improvement is shown in 12 patients. Two patients showed no change. *b* = before treatment, *a* = after treatment, *d* = difference

Pat. no.	Duration of sympt. (years)	Hearing loss	Glyc. test	dB PTA			Speech %			PTC scores					
										500 Hz			2 000 Hz		
				b	a	d	b	a	d	b	a	d	b	a	d
1	1	Ascend	+	55	18	37	87	100	13	-2	82	84	48	88	40
2	2	Ascend	-	45	18	27	96	100	4	0	48	48	84	86	2
3	8	Asc/													
		desc	-	42	32	10	86	100	14	8	62	57	-10	28	38
4	10	Asc/													
		desc	-	60	25	35	46	78	32	46	78	32	48	52	4
5	4	Flat	-	55	52	3	55	50	5	22	22	0	20	20	0
6	4	Flat	-	55	55	0	50	55	5	22	22	0	34	30	-4
7	4	Flat/													
		desc	+	65	27	38	62	98	36	22	80	58	22	66	44
8	5	Flat/													
		desc	-	58	52	6	62	98	36	14	38	24	20	44	24
9	5	Flat	+	60	32	28	52	92	40	-2	48	50	-6	42	48
10	6	Flat	-	57	42	15	50	78	28	22	44	22	-2	34	36
11	8	Flat	-	62	37	25	80	96	16	64	94	30	16	34	18
12	15	Flat	-	50	27	23	70	100	30	8	56	48	60	70	10
13	15	Flat	-	42	22	21	78	100	22	38	74	36	14	38	24
14	15	Flat	-	50	40	10	80	100	20	34	80	46	8	42	34

hearing was obtained within one month from the start of the pressure applications. In some patients, however, continuing improvement was observed over a period of 4 months.

Fig. 1 outlines the development of the hearing loss for 8 patients during the period of a pre-treatment observation (12 months), and after the start of pressure exposure (4 months). In Table I the results concerning the hearing parameters are shown for the 14 patients. The results presented in this table were obtained just before the start of pressure applications and after the hearing improvement appeared to have stabilized. In the 2 patients who did not show any change in hearing parameters the results are given after 2 months of pressure application.

The average improvement in PTA, for all 14 patients, was 20 dB. The average difference in speech discrimination scores was 21%. Average improvements in the PTC scores at test frequencies of 500 and 2 000 Hz were 48 and 24 units, respectively. The differences in hearing thresholds for the pure-tone frequencies of 500, 1 000 and 2 000 Hz are presented separately in Fig. 2. The average difference at 500 and 1 000 Hz was 24 dB and at 2 000 Hz, 12 dB.

Repeated measurements of PTCs during exposure to pressure changes allowed step-by-step observations of the change in the frequency resolution. In Fig. 3, the improvement in the PTCs at test frequencies of 500 and 2 000 Hz was followed over a period of 3 weeks in patient no. 1. The transformation of the PTC curve at 500 Hz (Fig. 3 A) from a complete disintegration in shape with an inverted peak, to the PTC curve approaching normal, is illustrated. The change in frequency selectivity was related to a substantial improvement in pure-tone audiometry at this frequency. An apparent improvement in the frequency selectivity at 2 000 Hz was also recorded in this patient (Fig. 3 B), though only a slight change in the

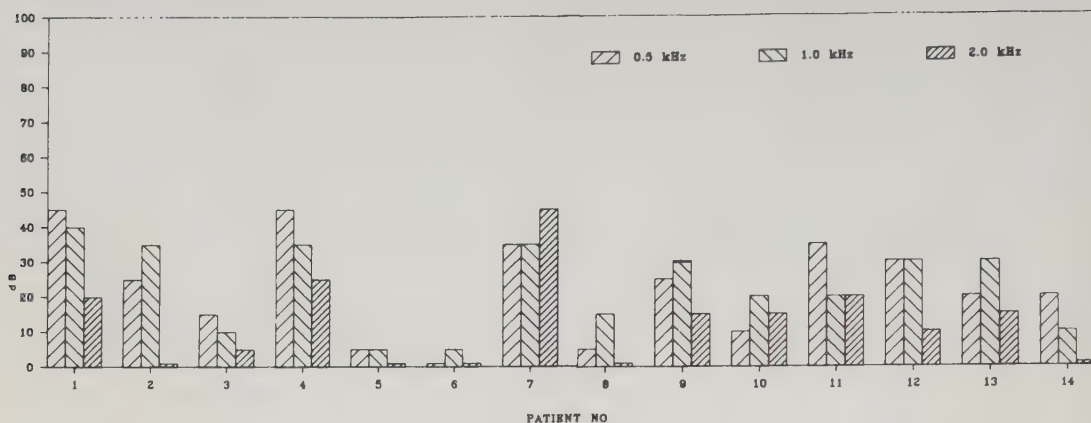


Fig. 2. The change in hearing threshold levels at 500, 1000 and 2000 Hz are shown for all patients. In 11 patients the improvement was >10 dB PTA. In 1 patient the improvement was <10 dB PTA. In 2 patients no change in PTA was observed.

pure-tone thresholds could be observed at this frequency (Fig. 3C). Fig. 4 illustrates the change in frequency selectivity function in patient no. 7, over a period of 3 months. A gradual improvement in the shape of the PTCs at test frequencies of 500 and 2000 Hz can be seen (Fig. 4 A, B). The change in the PTCs was accompanied by an improvement in pure-tone thresholds (Fig. 4C). The noise-induced hearing impairment in the high frequency range remained unaffected by pressure changes.

The question of whether the differences in hearing function recorded before and after the exposure to pressure changes became significant was studied by means of hypothesis testing. The null hypothesis, $H(0)$, "no difference in the hearing parameters before and after exposure to pressure changes", was tested against an alternative hypothesis, $H(1)$, "a difference in hearing parameters before and after the pressure applications". The Wilcoxon test was used. The null hypothesis, $H(0)$ could be rejected for all parameters (PTA, speech discrimination scores and PTC scores at 500 and 2000 Hz), at the 99% confidence level in favour of the alternative hypothesis, $H(1)$, with a 1% probability of being wrong in so doing.

DISCUSSION

In the management of Meniere's disease, the psychosomatic aspects of the disorder have frequently been emphasized (20, 21). Although no particular personality profile could be identified in the patients, a close correlation between stress-factors and intensity of symptoms has been indicated (22).

Irrespective of the treatment method used, similar rates of improvement with regard to dizziness and fullness have usually been reported. These observations suggest that the effects of a placebo should certainly be considered in the evaluation of the results of treatment (23, 24).

In a well-documented study the results of sac shunt and mastoidectomy operations were compared by Thomsen et al. (7) in a double-blind trial. It was found that both surgical methods had a beneficial effect on fullness and vertigo. However, no significant difference could be demonstrated between the active and the placebo group. No certain effects on hearing levels could be established in either the active or the placebo group. Despite de-

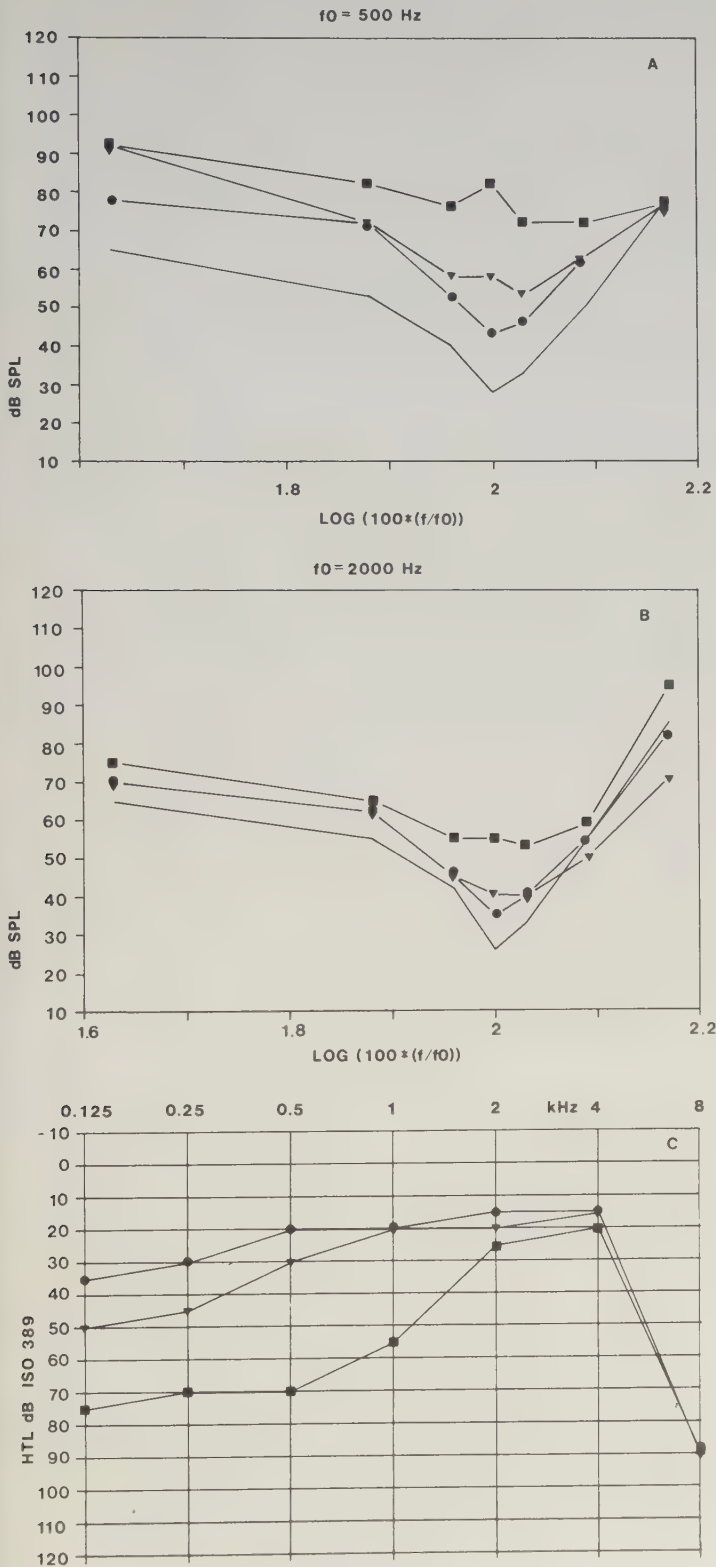


Fig. 3. PTCs and pure-tone audiograms from a single patient (no. 1) are shown. The change in frequency selectivity during pressure application is illustrated by PTCs at 500 (A) and 2000 Hz (B) test frequencies. Changes in hearing threshold levels are shown in (C). Start of pressure application (■—■), after 1 week (▼—▼) and after 3 weeks (●—●). 'Reference' PTC (—).

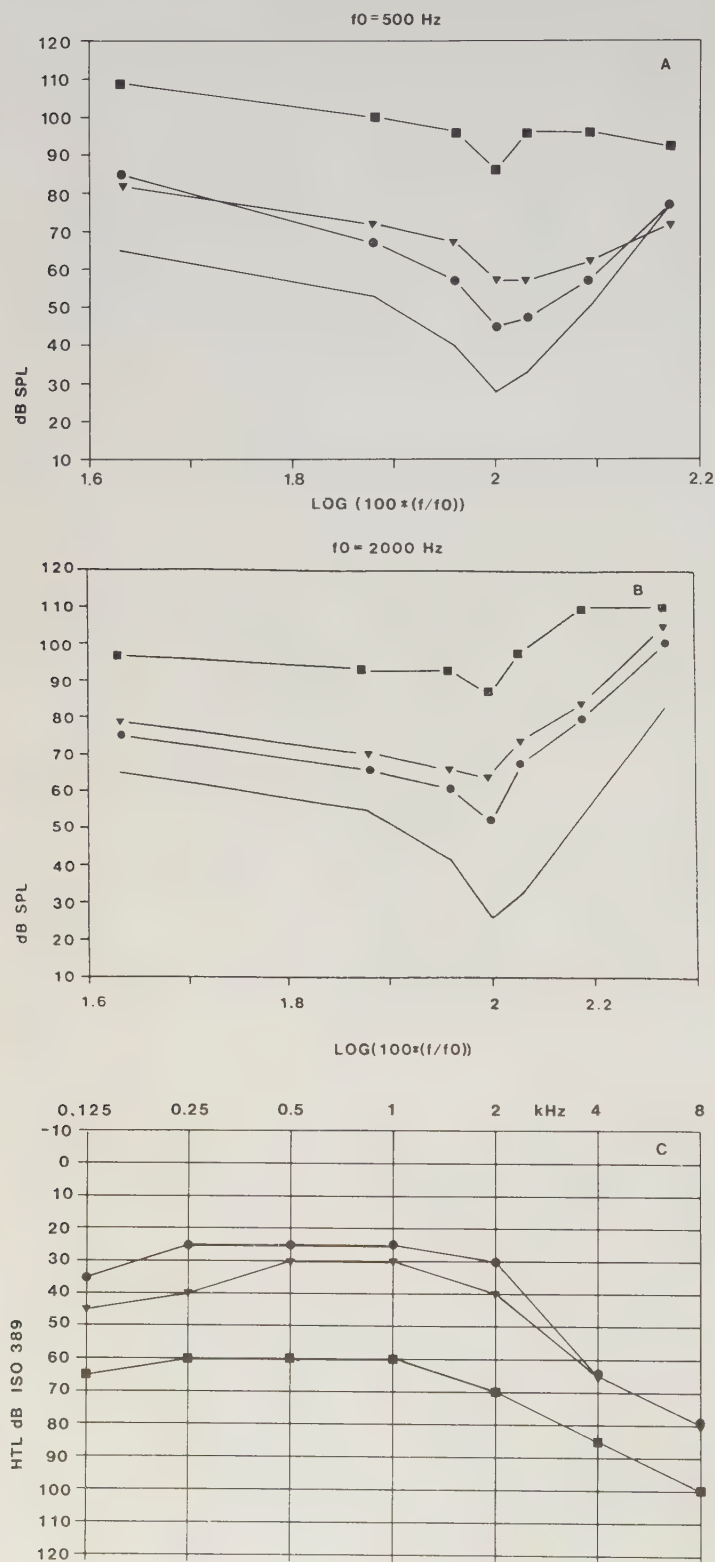


Fig. 4. PTCs from patient no. 7, at test frequencies of 500 Hz (A) and 2000 Hz (B). The sharpening in the frequency selectivity obtained during the period of pressure application is illustrated. The corresponding hearing levels are illustrated in (C). PTCs before the start of pressure application (■—■), after 1 month (▼—▼) and after 3 months (●—●). 'Reference' PTC (—).

velopments in inner ear surgery in Meniere's disease, no conclusive results regarding hearing levels have been demonstrated and it is commonly agreed that vertigo is the major indication for surgery (5, 25).

In the present study, an open method of investigation had to be chosen since the procedure of pressure application involved repeated calibrations of pressure levels in the individual patient. The question of influence of pressure changes on the hearing function was studied during a predetermined period of time. In order to strengthen the clinical implications of such a study, we focused on hearing function only and detailed serial measurements of this variable were performed. An improvement in hearing threshold levels of >10 dB PTA was found in 11 patients after exposure to the pressure changes. The average improvement over all patients was 20 dB PTA. Considering the period of pre-treatment observations, these changes seem unlikely to be caused by spontaneous fluctuations. The sensitivity to pure tones is, however, a crude measure of the hearing function and does not fully describe the nature of the sensorineural hearing loss of cochlear origin. Although speech discrimination is considered to be a more representative measure of the cochlear function, speech discrimination measurements contain other elements of auditory function and represent a sum of responses to the whole audible frequency spectrum.

Hearing loss in Meniere's disease is a particular form of cochlear impairment where decreased ability to analyse a complex sound and distortion of the signal are considered to be characteristic. Studying the hearing loss in Meniere's disease, Opheim & Flottorp (26) found abnormal aural harmonic thresholds, while Bonding (27) demonstrated a widening of the critical band and defective interaction between adjacent filters. Poor frequency selectivity was demonstrated in patients with Meniere's disease by Zwicker & Schorn (19). These phenomena, however, are not equally distributed along the cochlear partition but are related to changes in the mechanical properties of the basilar membrane (4, 14).

In the present investigation, the frequency selectivity function was studied at test frequencies of 500 and 2000 Hz using PTCs. Analysis of the general shapes of the PTCs showed that the curves from the patients before treatment were broader and shallower, indicating the inner ear's inability to differentiate between the masker and the test tone. PTCs with such shapes indicate that a substantial amount of noise passes through the auditory filter together with the signal. This observation probably accounts for at least part of the decreased ability to discriminate speech. As the shapes of the PTCs improved, the slopes of the curves became generally steeper and the vertical distance between the test-tone level and the masker levels increased, indicating an increased ability of the inner ear to sort out one tone from the other on the basis of frequency difference.

Estimation of the amount of change in the inner ear selectivity function could be made by the method of quantifying the PTCs in terms of scores. In order to establish whether a change in frequency selectivity could be considered significant, results of the variation in scores due to the technique of measurement were used (16). It was inferred that a change in scores >8 –10 units was significant at the 95% confidence level. Changes larger than this were found at the test frequency of 500 Hz in all the patients who improved, viz. in 12 of 14. At the test frequency of 2000 Hz, 9 out of 14 patients showed significant improvement in frequency selectivity. This change was also found in patients where no change in the pure-tone threshold level could be measured at 2000 Hz.

The average difference in scores was greater at 500 than at 2000 Hz. The results may be compatible with the fact that the frequency selectivity around the higher frequency is reduced by age- and noise-induced changes. The improvement in frequency selectivity scores was accompanied by an improvement in speech discrimination. Although the speech discrimination scores increased to 100% in most patients, none showed maximum values of frequency selectivity scores. The system of scores was developed on the basis of results ob-

tained from a homogeneous group of normal-hearing young subjects. The average age of patients in this study was 50 years. Age-dependent differences in frequency selectivity are being further investigated (unpublished data).

Quantified measurements of the inner ear frequency selectivity seem to represent a sensitive way of studying hearing function. The method also allows for a better understanding of the changes in hearing function in Meniere's disease. Apart from an improvement in sensitivity to pure tones, the patients also showed an improvement in frequency selectivity. The results show a considerable resistance of the inner ear end-organs to the mechanical volume/pressure disturbances caused by hydrops.

Changes in hearing quality found in the patients may be interpreted as an improvement in the functioning of the basilar membrane and an improvement in conditions for stimulation of the hair cells. The endolymphatic duct and sac, the stria vascularis and the surrounding tissues may be considered as possible routes for reduction of the endolymphatic fluid volume under an increase in the perilymphatic pressure. It may also be supposed that transmission of pressure changes may influence mechanisms responsible for the reabsorption of the endolymphatic fluid.

Although an adequate explanation of the underlying hydrodynamic mechanisms cannot be offered yet, the results indicate that the overpressure method has a therapeutic potential, which should be explored further.

ACKNOWLEDGEMENT

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AIR-BONE GAP IN MENIERE'S DISEASE AFTER EXPOSURE TO OVERPRESSURE

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ABSTRACT

Equal loss in sensitivity for air and bone conduction and poor speech discrimination are considered characteristic for the hearing impairment in Meniere's disease. In connection with exposure to pressure changes applied in the middle ear, an air-bone gap was disclosed in 16 out of 19 patients with advanced Meniere's disease. The appearance of the air-bone gap was associated with with an improvement in speech discrimination scores. The shapes of the psychoacoustic tuning curves from the patients with the air-bone gaps showed an improvement in frequency resolution. The curves were, however, elevated in thresholds which indicated an attenuation of the sound stimuli. Therefore, the relative change in sensitivity of the bone conduction was interpreted as an early sign of improvement in the inner ear hydrodynamic properties, caused by exposure to pressure changes. The results suggest a transformation of the hearing impairment from purely sensorineural to that with an intracochlear conductive component.

Key words: Meniere's disease, air-bone gap.

INTRODUCTION

Meniere's disease represents a special form of inner ear dysfunction which is caused by a disturbance in the inner ear fluid balance (Hallpike & Cairns, 1938). Results from experiments on animals and cochlear models support the hypothesis that the hearing loss in Meniere's disease is the result of the mechanical effect of increased endolymphatic pressure on the basilar membrane (Tonndorf, 1975; Allen, 1983). The hearing loss shows all the features of a sensori-neural impairment, although some observations indicate that its nature may be more complex. Morphological investigations on temporal bones, from patients with advanced stages of Meniere's disease, have shown distensions and ruptures of the membranous labyrinth but often well-preserved hair cells in the organ of Corti (Schuknecht, 1963).

Mygind (1947) defined the hearing impairment in Meniere's disease as a sound conductive deafness due to deformation of the cochlear membranes. An air-bone gap has occasionally been observed in the early stages of Meniere's disease. A restraint of sound conduction within the inner ear fluids has been proposed as a possible explanation of this phenomenon (Goodhill & Harris, 1979).

Kitahara et al. (1975) registered an improvement in bone conduction in connection with the opening of the endolymphatic sac in patients with Meniere's disease. The measured improvement was up to 10 dB and was directly dependent on the flow of the endolymph.

Experiments carried out by von Békésy (1932) on sound conduction have contributed to the understanding of mechanisms of bone conduction. He demonstrated that the bone-conducted sound directly stimulated inner ear fluid motion in the cochlea. Bárány (1938) described the middle ear components of bone conduction. Tonndorf (1976) has described these two components in more detail as well as a third, outer ear component, in bone conduction. The middle ear component is mainly determined by ossicular inertia but also influenced by mechanical loading of the ossicular chain, at the ear drum as well as at the oval window.

Because of this complex signal transmission, uncertainty has always been associated with measurements of bone conduction. Its application in the assessment of hearing function has therefore been limited (Bárány, 1938; Carhart, 1950). In the investigation of the effects of ambient pressure changes on hearing function in Meniere's disease, our attention has been drawn to the bone-conduction thresholds, because of air-bone gaps observed after exposure to pressure

changes. These findings were often associated with an improvement in speech discrimination scores and a reduction in hearing distortion (Densert & Densert, 1982). It therefore seemed probable that the appearance of the air-bone gap could reflect a change in the inner ear function and as such deserved a closer investigation.

The aim of this study was to investigate the significance of the audiometric findings of air-bone gaps in patients with Meniere's disease who had been exposed to pressure changes.

SUBJECTS AND METHODS

The study comprised 19 patients with Meniere's disease. Diagnosis was based on history and otoneurological examination. The audiological tests included measurements of pure-tone hearing thresholds, speech discrimination scores, stapedius reflex thresholds and psychoacoustic tuning curves (PTC's).

The average duration of symptoms was seven years. The longest duration was 15 years (3 patients), the shortest one year (1 patient). In 14 patients, the average pure-tone hearing loss, PTA, (500, 1000 and 2000 Hz) was in the range 45 to 65 dB. Two of these patients showed an ascending type of audiogram, two showed an ascending/descending type of audiogram and 10 patients had a flat or flat/descending type of audiogram.

In the remaining five patients, the PTA exceeded 65 dB, with a mean of 80 dB. The hearing loss was of flat or flat/descending type.

Audiometric testing procedures

A Madsen OB 70 audiometer was used for measurements of air and bone-conducted thresholds. A Danplex AS 72 audiometer providing narrow-band noise was used for masking of the contralateral ear when measuring the psychoacoustic tuning curves.

The system was calibrated in accordance with re. ISO 389, 1975. The bone conduction measurements were made by placing the bone vibrator, Radioear B 71, on the mastoid process. The exact position of the vibrator was established by finding the place of best conduction. The bone conduction audiometer was calibrated by means of an artificial mastoid, Bruel & Kjaer type 4930, according to IEC 373, and with reference to ISO/DIS 7566.

Measurements of psychoacoustic tuning curves, PTC's, were obtained by means of a simultaneous masking technique according to Zwicker & Schorn (1978) at test frequencies of 500 and 2000 Hz. Quantitative evaluation of the PTC's was made using a computerized method (Densert et al., 1986).

Pressure application procedure

A specially constructed generator was used for the induction of pressure changes. The static pressure level and the amplitude of the sinusoidal pressure waves could be adjusted separately.

Pressure changes were administered in the ear canal. A transmyringal Teflon tube was inserted into the tympanic membrane in order to facilitate transmission of the pressure changes to the middle ear. For details see Densert (1986). The period of exposure to pressure applications was less than four months for 17 patients and extended for 12 months for two patients.

RESULTS

The air-bone gap appeared early after the commencement of pressure applications - in the majority of patients after two to three weeks.

The appearance of the air-bone gap was associated with a decrease in the feeling of fullness in the ear and with an improved sound quality. The size of the air-bone gap varied during the period of exposure to pressure applications. It was generally largest in the beginning, because of a relative improvement in the bone conduction, but became smaller as the air conduction thresholds also improved.

The air-bone gap was disclosed in 16 out of the 19 patients included in the study. In 3 patients no significant air-bone gap could be recorded. Two of these 3 patients did not show any significant change in either pure-tone audiometry or speech discrimination scores after exposure to pressure changes. The results from the audiological tests are shown in Table I. The values of the air-bone gaps given are the maximum values observed in the patients during the exposure to pressure changes. The values for the air-bone gap before exposure to pressure applications are also given. In the patients showing hearing losses larger than 75 dB, no reliable bone-conduction thresholds could be determined. The corresponding results of measurements of speech discrimination scores and of PTC's are shown in the same table. The results of the PTC measurements are presented in terms of scores where a score of 100 corresponds to the average normal PTC configuration. The method to quantify the PTC's is described in detail in Densert et al. (1986).

The magnitude of the air-bone gap could be considered significant at the 95% confidence level (2 SD), when it exceeded 15 dB. This inference is based on yet unpublished test-retest measurements of air and bone-conduction thresholds on 60 subjects with different hearing pathologies.

The lower limit for a significant air-bone gap, 15 dB, corresponds to $2 \cdot 1/\sqrt{2}$ times the largest standard deviation for test-retest difference of air-bone gap obtained in that study. An air-bone gap > 15 dB was found in 18 patients at 250 Hz, in 13 patients at 500 Hz, in 14 patients at 1000 Hz and in only 4 patients at 2000 Hz. The largest air-bone gaps were observed at 250 and 500 Hz and the highest value was 50 dB. The air-bone gaps were smallest at 2000 Hz.

The mean value of the air-bone gap before exposure to pressure applications, was 2.6 dB. The mean air-bone gap after exposure was 17.2 dB. The difference between the mean gaps before and

TABLE I

Pat no.	duration of sympt. years	PTA dB	air-bone gap					speech discr.	PTC scores	
			250	500	1000	2000	Hz		500	2000 Hz
1	1	b	55	15	5	0	0	86	-4	48
		a	25	20	20	15	0	98	72	104
2	2	b	40	15	5	0	0	96	0	84
		a	18	20	0	5	0	100	48	90
3	8	b	42	10	0	10	5	86	8	-10
		a	35	30	20	20	0	100	60	30
4	10	b	60	0	10	-5	-5	46	46	48
		a	35	30	25	20	0	98	86	64
5	4	b	55	10	5	10	0	55	22	20
		a	52	15	5	10	0	50	22	20
6	4	b	55	0	10	5	-5	56	22	34
		a	55	0	0	5	0	50	22	30
7	4	b	65	0	10	5	0	62	22	22
		a	45	40	30	20	15	100	52	60
8	5	b	55	0	0	5	0	62	14	20
		a	50	20	15	20	10	98	38	44
9	5	b	60	5	0	5	0	50	-2	-6
		a	55	30	30	20	5	98	42	45
10	6	b	57	0	0	10	-5	50	22	-2
		a	55	35	15	15	15	86	50	32
11	8	b	62	15	0	0	0	80	64	16
		a	45	30	20	25	10	98	96	36
12	15	b	50	5	-10	0	0	70	8	60
		a	30	20	5	5	5	96	56	70
13	15	b	45	20	0	-10	-5	78	38	14
		a	35	20	10	10	0	92	70	38
14	15	b	50	10	5	5	0	80	34	8
		a	45	20	20	15	5	100	74	30
15	4	b	80	0	0	0	0	42	-	-
		a	60	50	40	30	20	100	45	42
16	5	b	85	0	0	0	0	4	-	-
		g	65	30	30	25	10	72	10	12
17	6	b	75	15	0	10	0	42	-	-
		a	50	40	20	30	0	98	58	46
18	7	b	70	10	0	0	0	48	-	-
		a	35	30	30	15	15	100	90	96
19	10	b	85	-	-	-	-	76	-	-
		a	45	30	10	15	0	92	60	68

b=before, a=after exposure

Data comprising results on the hearing parameters in 19 patients. Air-bone gaps exceeding 15 dB are considered statistically significant.

after exposure was found to be statistically significant (paired T-test, $p < 0.001$).

The appearance of the air-bone gap was associated with an increase in the speech discrimination scores. The measurements of PTC's showed that the frequency selectivity improved concurrently with the appearance of the air-bone gap. The shapes of the PTC's indicated better frequency resolution, although the curves remained elevated in thresholds.

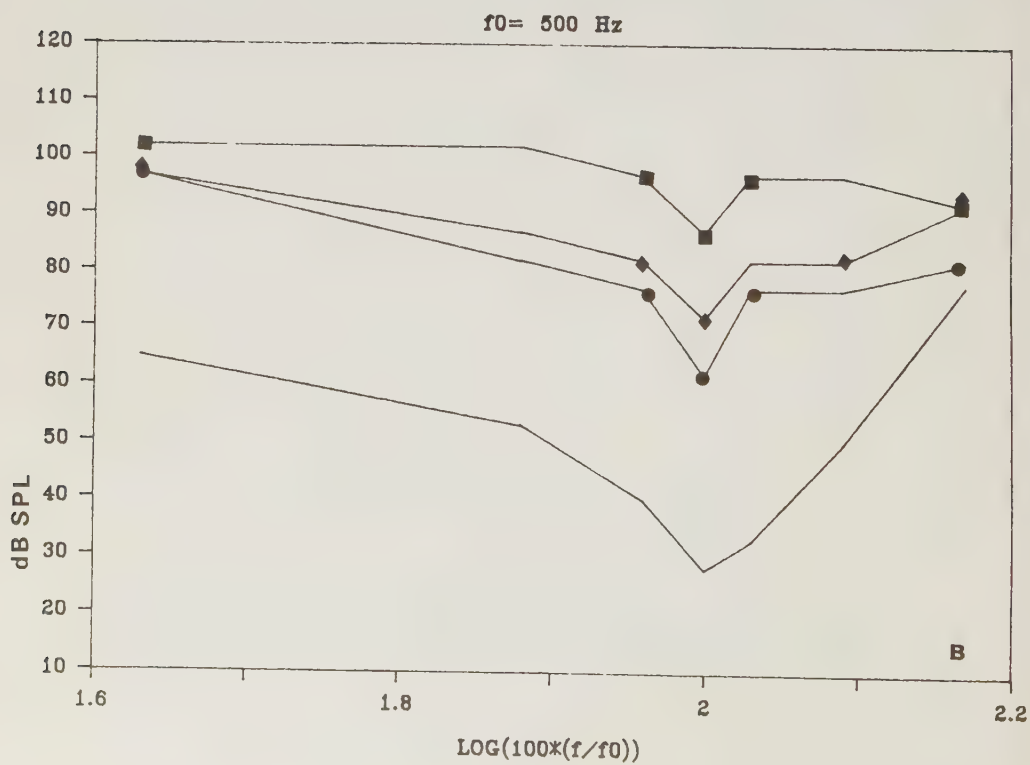
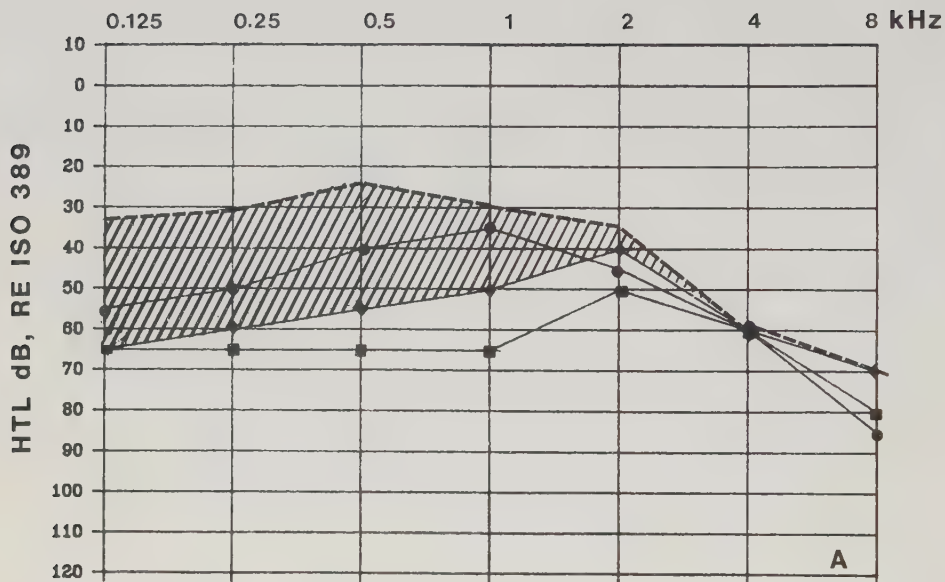
Possible correlations between different hearing parameters were tested by means of linear regression analysis with the results shown in Table II. Differences in the hearing parameters before and after exposure to pressure changes were the variables tested. Association between the variables could be considered significant, at 95% confidence level, when the values of the correlation coefficient exceeded 0.453. Such association was found between differences in the speech discrimination scores and differences in the mean air-bone gaps. Significant correlation was also found between the increase in the PTA and changes in the PTC scores at 500 and 2000 Hz, and between differences in the PTC scores at 500 and 2000 Hz.

For the remaining sets of variables, the null hypothesis, $H_0 =$ "the parameters were unrelated", could not be rejected, at a stated level of significance.

TABLE II

CORRELATION MATRIX					
VARIABLES:					
1 D PTA	1.000				
2 D GAP	0.295	1.000			
3 D SPEECH	0.301	0.855	1.000		
4 D PTC 500	0.702	0.237	0.228	1.000	
5 D PTC 2000	0.577	0.447	0.337	0.810	1.000
	1 D PTA	2 D GAP	3 D SPEECH	4 D PTC 500	5 D PTC 2000
CRITICAL VALUE = 0.453					

RELATIONSHIPS BETWEEN THE DIFFERENT HEARING VARIABLES ARE SHOWN IN TERMS OF CORRELATION COEFFICIENTS. THE VARIABLES ARE RELATED IF THE CORRELATION COEFFICIENT IS > 0.453 . D INDICATES A DIFFERENCE IN THE HEARING PARAMETERS BEFORE AND AFTER EXPOSURE TO PRESSURE CHANGES.



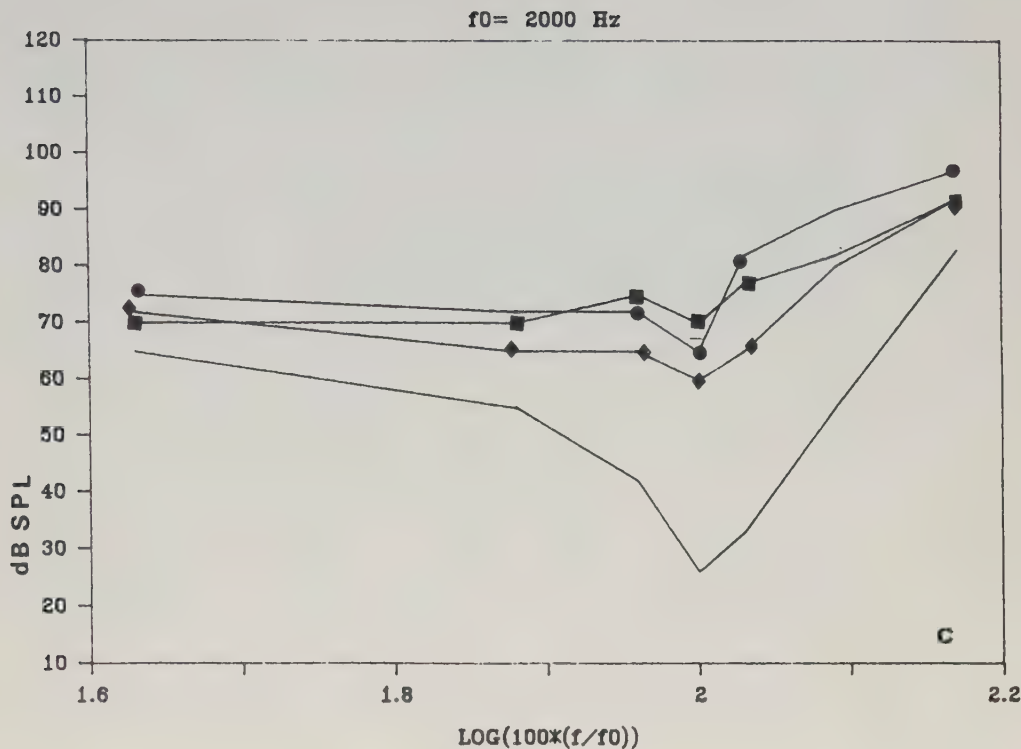


FIGURE 1

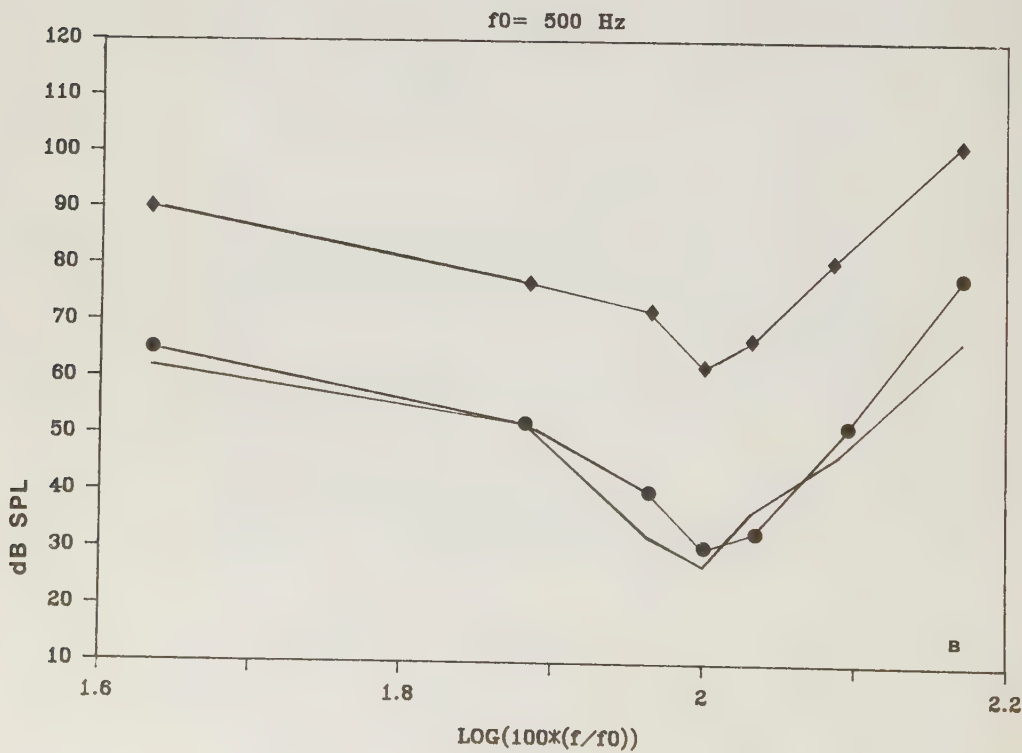
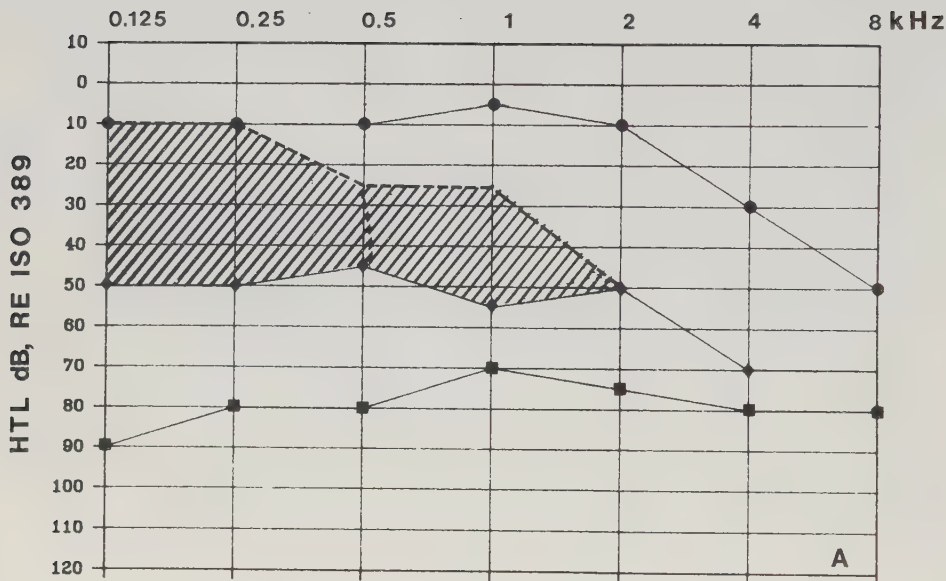
Pure tone audiograms (A) and corresponding PTC's (B, C) from patient no. 9. The air-bone gap, indicated by the shaded area (A), was most pronounced after 1 month of pressure applications. Further improvement in hearing thresholds was found one month later.

The improvement in frequency selectivity at 500 Hz is shown in B. At 2 000 Hz (C) the change in frequency selectivity is less apparent.

Fully drawn curves in B and C correspond to the average PTC configuration.

Air conduction: start of pressure application (■—■), after 1 month (◆—◆) and after 2 months (●—●).

Bone conduction is shown after 1 month of pressure application (---).



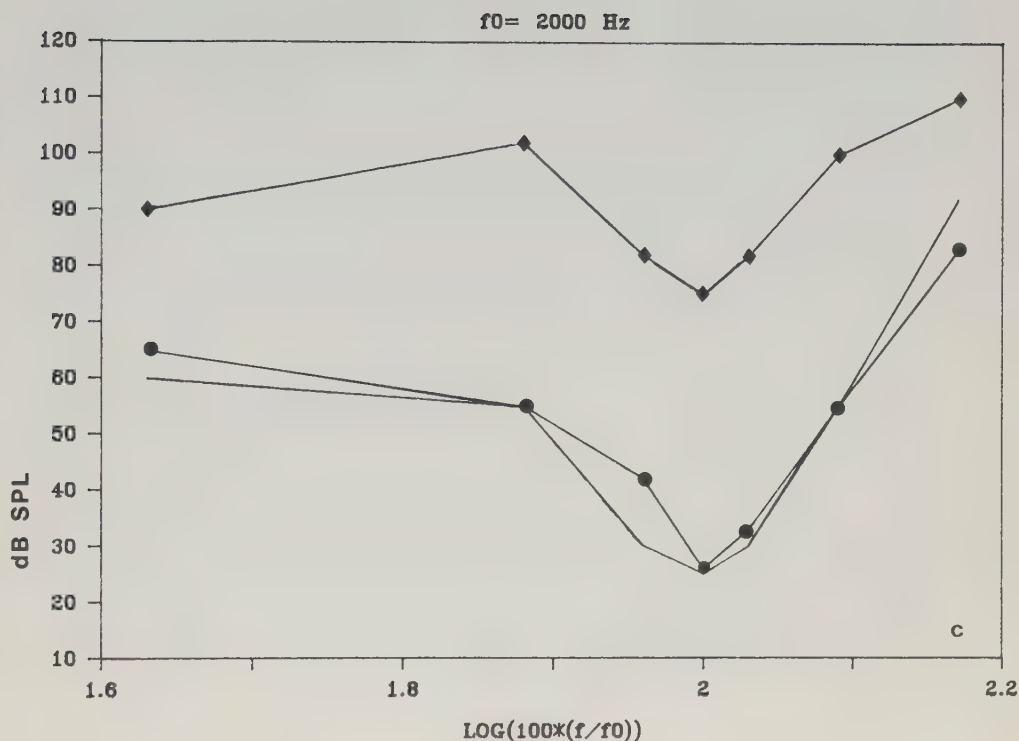


FIGURE 2

A substantial air-bone gap is shown in patient no. 17. The gap was maximal after 3 months of pressure exposure and is indicated by the shaded area (A). The hearing threshold levels were later normalized.

PTC's corresponding to changes in the hearing thresholds are shown in B and C. The shapes of the PTC's indicate a conductive type of hearing impairment. Because of the advanced hearing loss PTC data were not available before the start of pressure application.

Start of pressure application (■—■), after 3 months (◆—◆) and after 6 months (●—●).

Bone conduction is shown after 3 months of pressure application (— — —).

The stapedius reflex thresholds varied from 90 to 120 dB before the period of exposure. The thresholds remained essentially unchanged after the appearance of the gaps. In a few patients however, an average 10 dB lower thresholds were noted, as the hearing thresholds improved. In two patients, no stapedius reflexes could be elicited either before or after the exposure.

Figure 1 illustrates the air-bone gap in a 65 year old patient, one month after the start of pressure applications. The shapes of the PTC's indicate an improvement in frequency selectivity although there is only a slight change in the hearing threshold levels. One month later, further improvement in hearing function was observed. The improvement is less pronounced at 2000 Hz, probably because of an age-induced hearing impairment.

Figure 2 shows the substantial air-bone gap after 3 months of exposure to pressure applications. This patient showed a sensorineural hearing loss of 80 dB PTA before the start of pressure applications. Measurements of the PTC's could not be conducted prior to the pressure applications because of the poor hearing thresholds. As the hearing thresholds improved, the PTC's could be measured. The properties of the PTC's then indicated a restrain in sound transmission; a general elevation of the tuning curve with essentially normal frequency selectivity. The hearing tests performed some months later showed further improvement in hearing threshold levels and frequency selectivity, apart from the high frequency hearing loss which remained unchanged.

DISCUSSION

According to the classical experiments of von Békésy (1932), a travelling wave is created in the cochlea in the same way by air and bone-conducted sound. However, while the air conduction occurs via the middle ear transmission system alone, the bone conduction vibration gives rise to a stimulation of the cochlea via several transmission mechanisms. Experimental investigations have shown that bone conduction consists of a compressional bone conduction, reflecting the inner ear fluid response, (Tonndorf, 1976), a middle ear component caused by the relative motion of the ossicular chain and an outer ear component (von Békésy, 1941; Tonndorf, 1962). Bone conduction thresholds are thus influenced by factors other than the state of the cochlea and therefore are considered unfit as a single measure of the cochlear function (Bárány, 1938; Tonndorf, 1976).

Because of the uncertainties associated with measurements of bone conduction, observations of air-bone gaps in early cases of Meniere's disease, and sometimes during treatment (Densert & Densert, 1982), had not been fully understood. In the present investigation, assessment of the air-bone gap was made using results of test-retest investigations conducted on patients with different forms of hearing loss. It could be shown that a significant air-bone gap was found in the majority of patients included in this study. Correlation was found between an increase in the air-bone gap and an increase in speech discrimination scores measured at the time of maximal air-bone gaps.

Measurements of the PTC's provided adequate means for the estimation of changes in the inner ear function (Densert et al., 1986). The shapes of the PTC's from patients with an air-bone gap showed features similar to those obtained from patients with a middle ear impairment (Zwicker & Schorn, 1978). The PTC's thus showed an improved frequency resolution, although the curves were elevated in absolute levels.

The change in frequency selectivity, observed together with the improvement in bone-conduction thresholds, indicates a transformation in nature of the hearing loss. The purely sensorineural hearing loss acquired characteristics of a conductive impairment. The air-bone gaps indicated that the sound energy reached the inner ear receptors relatively more easily via bone than air conduction. Since the middle ear reflex thresholds were not influenced by the appearance of the conductive component, the reduction in sound transmission is likely to be located within the inner ear fluid system. The improved threshold levels for bone conduction may be explained by changes in either the inner ear or the middle ear component

of bone conduction or both. A single cause, namely a change in inner ear fluid conditions may influence both these components.

The results of the present investigation may be understood in the light of Tonndorf's (1975) experiments on cochlear models. According to his results, an increment in mass and stiffness of the cochlear partition causes an exponential displacement of the basilar membrane, which affects the function of the hair cells and adjacent nerve fibers. The nonlinear distortions which are characteristic for the hearing impairment in Meniere's disease (Flottorp, 1980), have been explained by such functional disturbances in the inner ear receptors. The changes observed in the inner ear function might indicate that the position of the basilar membrane and its related structures could partly be restored in patients with Meniere's disease exposed to pressure changes. A change in the inner ear hydrodynamic properties, resulting in better formation of the travelling waves and an improved pattern of stimulation of the hair cells might be the reason of improvement in cochlear function. However, since the cochlear partition may still be loaded with an excessive mass of endolymph, stimulation of the hair cells may require increased input levels at the oval window.

According to Zwislocki's (1953) experiments, the acoustic input impedance of the cochlea is, in addition to other factors, determined by the stiffness of the cochlear duct in the region of the oval window. This property may, in turn, be related to the amount of the endolymphatic fluid filling the scala vestibuli. The increased mass of the endolymph may explain the relative difference in energy input levels required for air and bone-conducted stimulation.

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